Improvement of Mechanical Properties and Life Extension of High Reliability Structural Components by Laser Shock Processing

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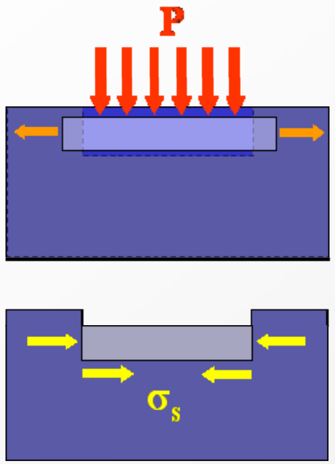
OUTLINE:

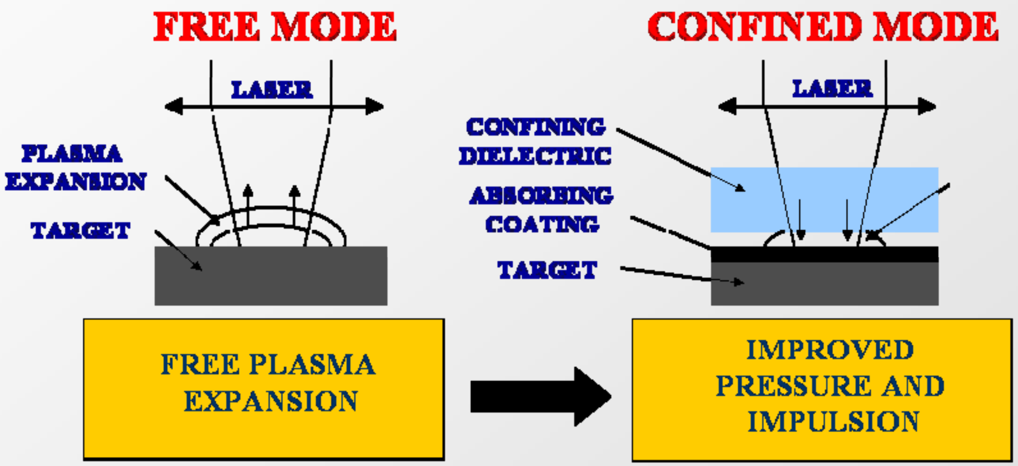
- Introduction. Fundamental Physics of Laser Shock Processing
- Experimental Procedure
- Experimental Results for Al2024-T351 and Ti6Al4V
  - Surface Roughness
  - Microstructure
  - Microhardness
  - Wear
  - Residual stresses
  - Fatigue crack growth
- Discussion and Outlook

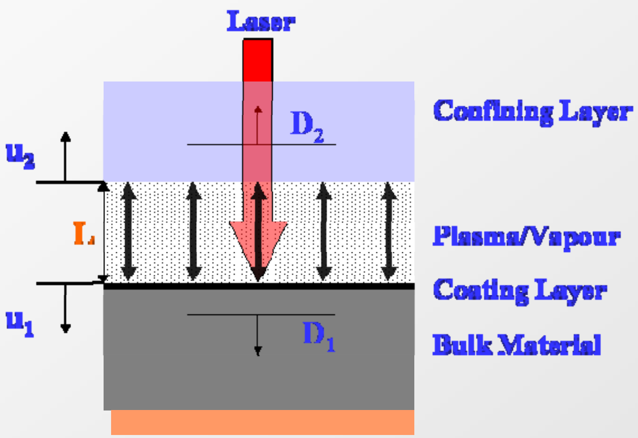
INTRODUCTION

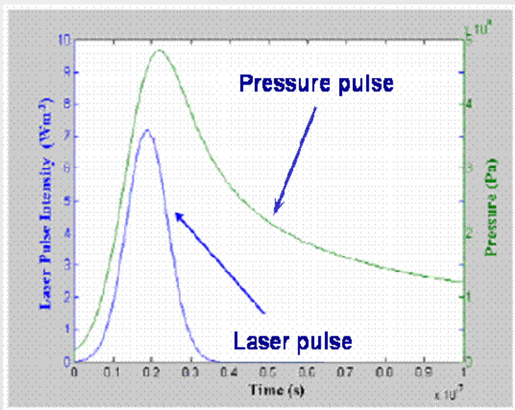
- **Laser Shock Processing (LSP) is developed as a technique allowing the effective induction of residual stresses fields in metallic materials allowing a high degree of surface material protection against fatigue crack propagation, abrasive wear, chemical corrosion and other failure conditions, what makes the technique specially suitable and competitive with presently use techniques for the treatment of heavy duty components in the aeronautical, nuclear and automotive industries.**
- **However, according to the inherent difficulty for the prediction of the shock waves generation (plasma) and evolution in treated materials, the practical implementation of LSP processes needs an effective predictive assessment capability coupled to a readily controllable experimental setup for a correct application of treatment parameters and an associate material properties characterization capability.**
- **Despite the availability of the LSP technique at laboratory level, practical developments at industrial level still need to be further accomplished.**
- **In the present communication, the practical LSP treatment and associate specimens characterization capabilities developed at CLUPM (Spain) are presented along with selected results obtained in two relevant aerospatial alloys (Al2024-T351 and Ti6Al4V).**

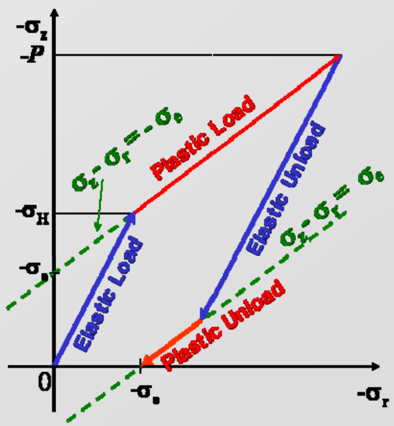
REMINDER OF LSP PHYSICAL PRINCIPLES (1/2)



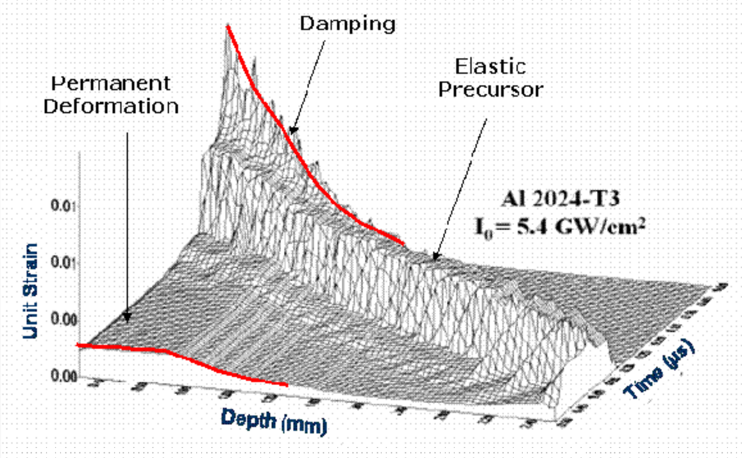


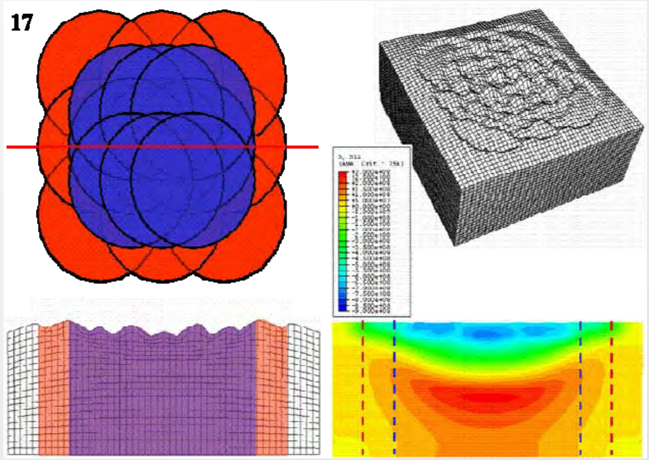


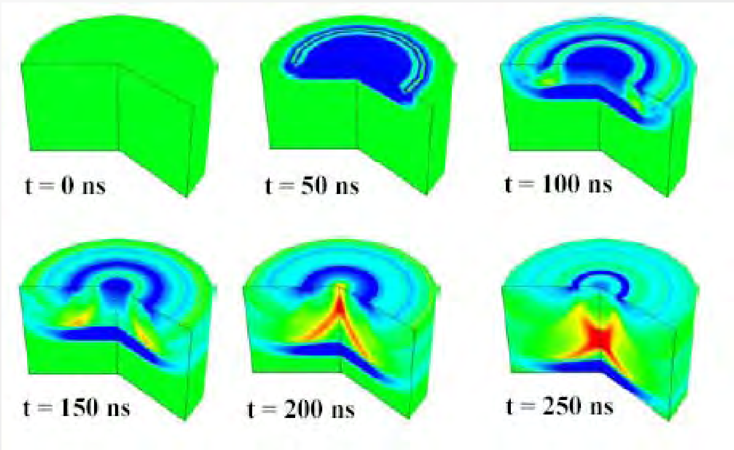


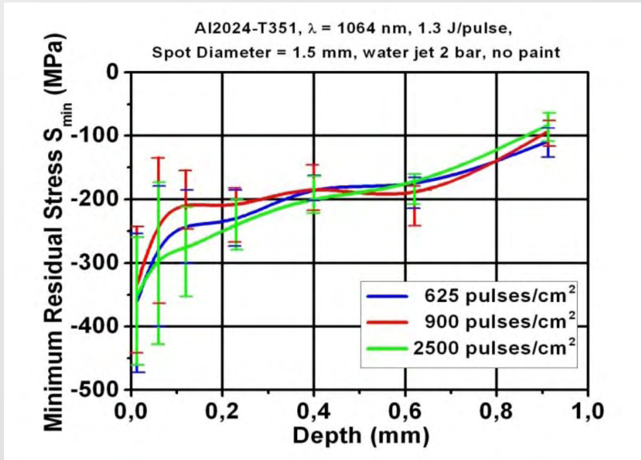


REMINDER OF LSP PHYSICAL PRINCIPLES (2/2)





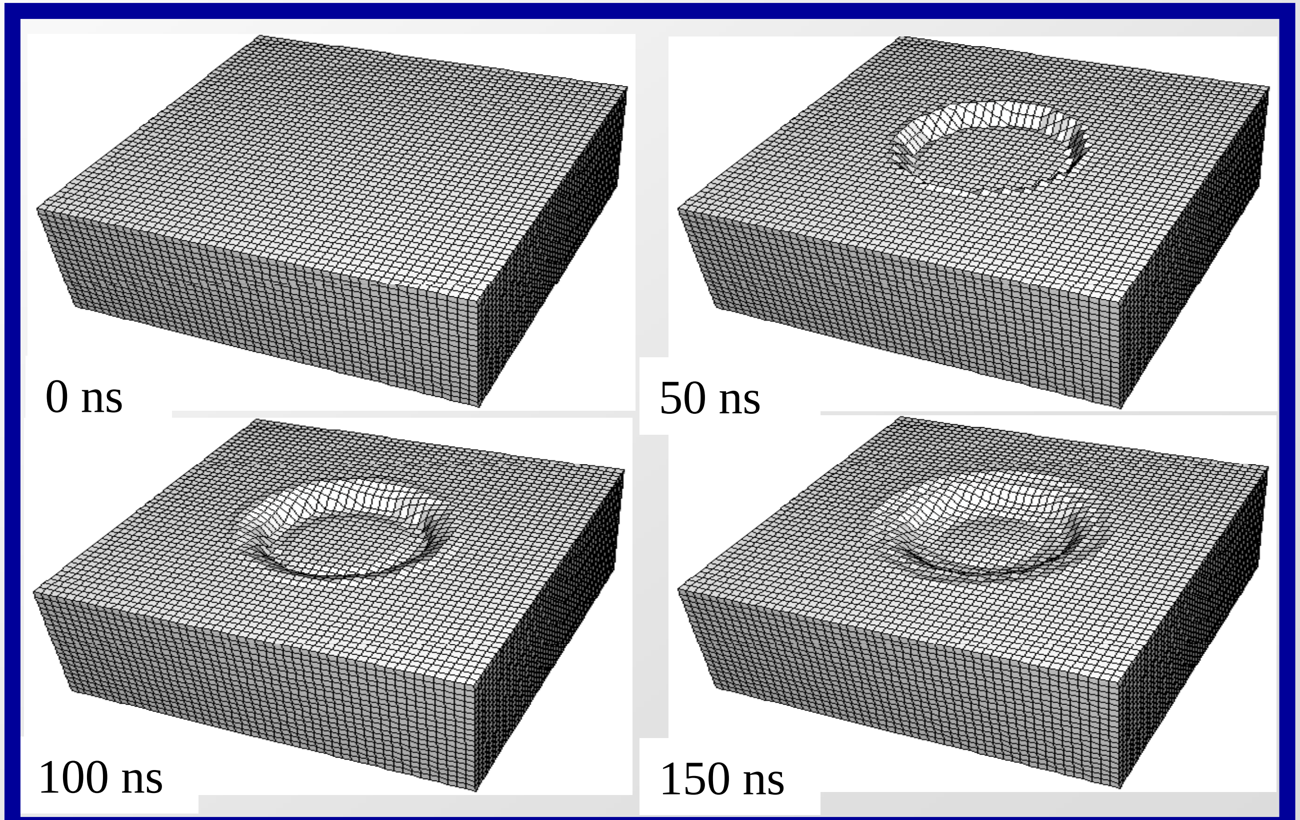




HARDSHOCK-2D Semi-infinite

Ti6Al4V

Nd:YAG (1064 nm)
P_{av}= 5,7 W/cm^2
Spot radius = 0.75 mm
FWHM = 0 ns
α = 0.15



Multiple shocks dynamic analysis

NUMERICAL SIMULATION RESULTS

HARDSHOCK-2D Semi-infinite

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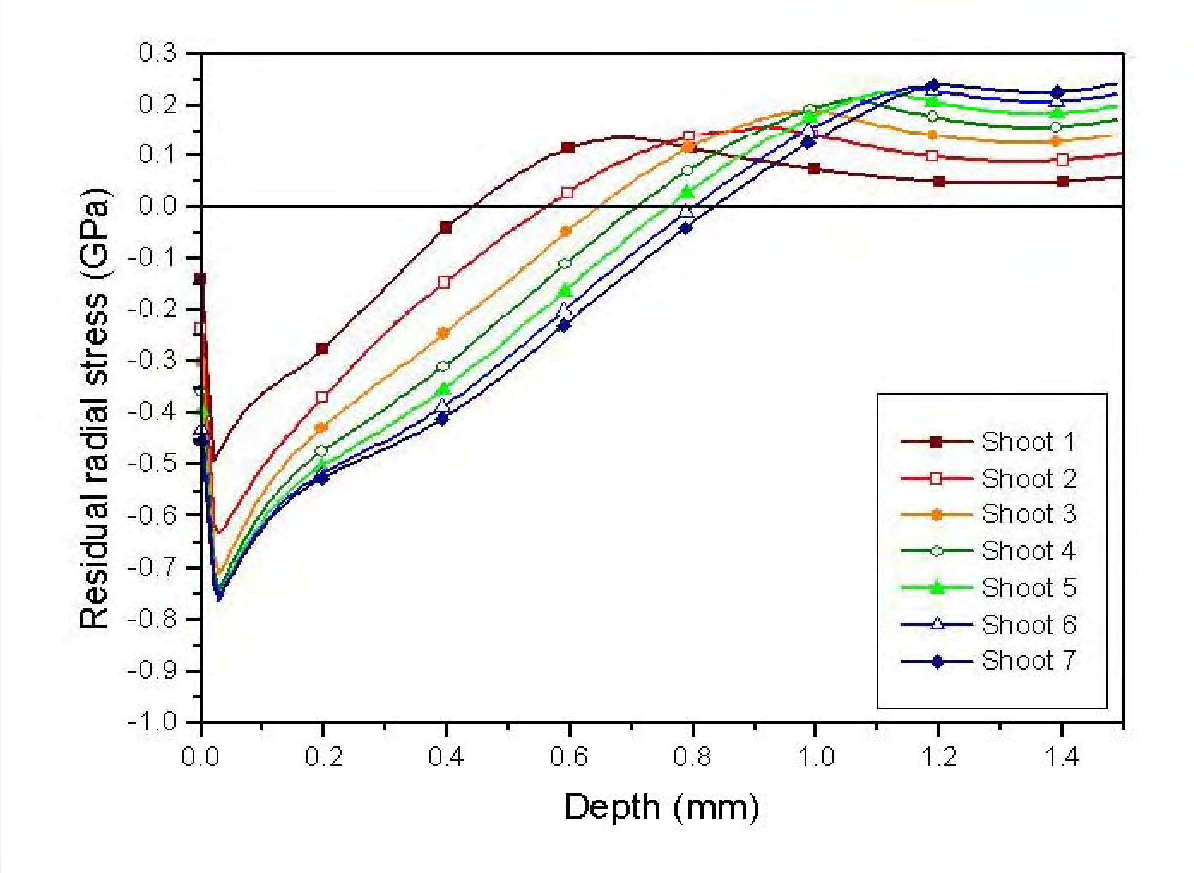

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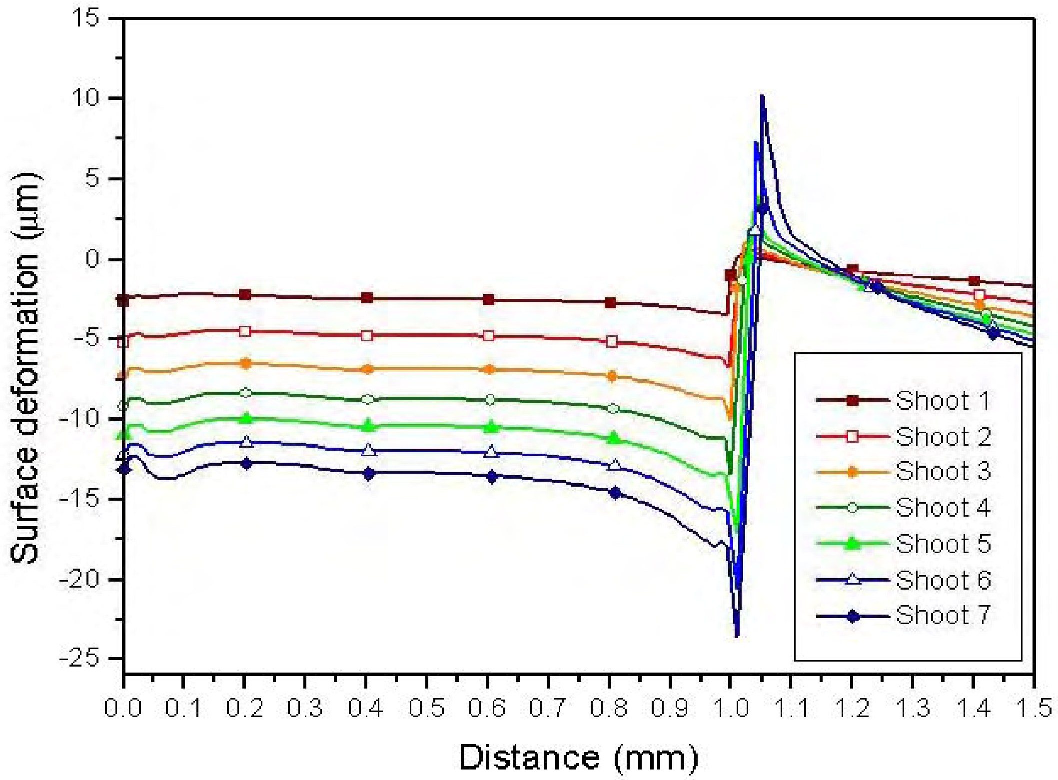


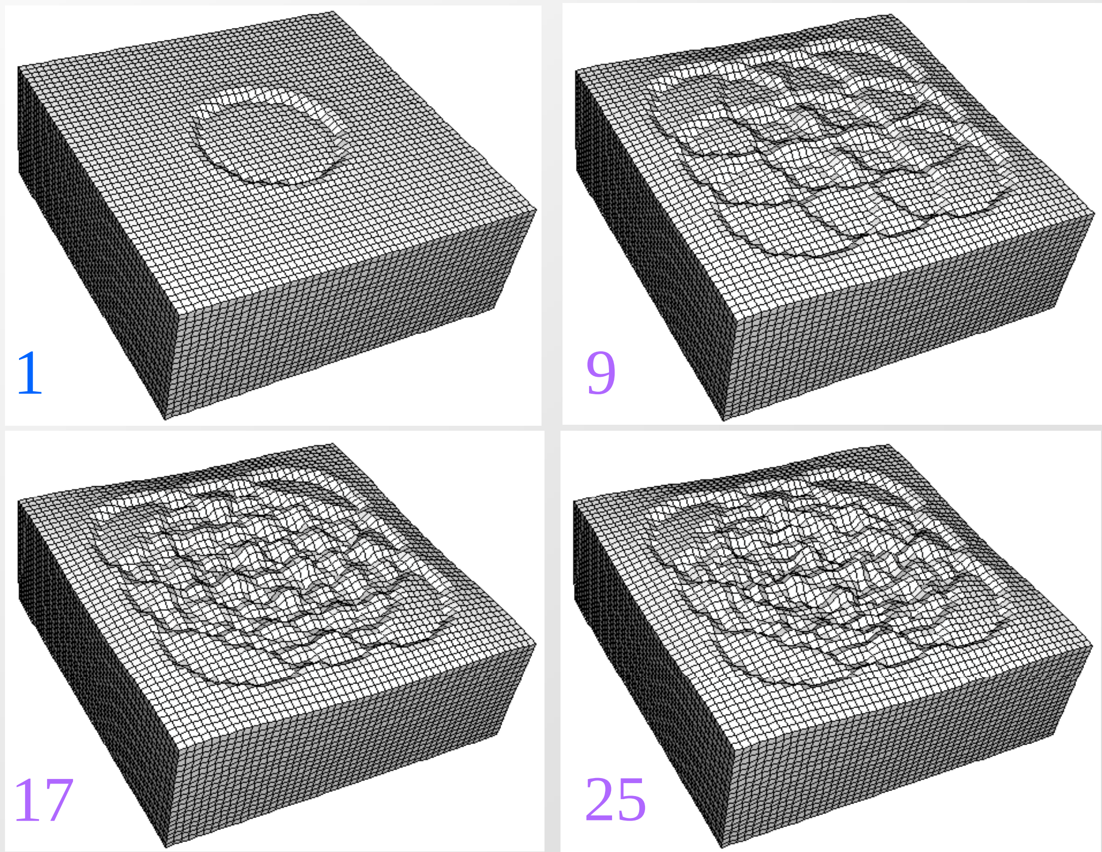
Multiple shocks dynamic analysis

NUMERICAL SIMULATION RESULTS

HARDSHOCK-3D (full scope)

Ti6Al4V

Nd:YAG (1064 nm)
P_{av}= 5,7 W/cm^2
Spot radius = 0.75 mm
FWHM = 0 ns
α= 0.15
Overlapping = 900/cm^2



NUMERICAL SIMULATION RESULTS

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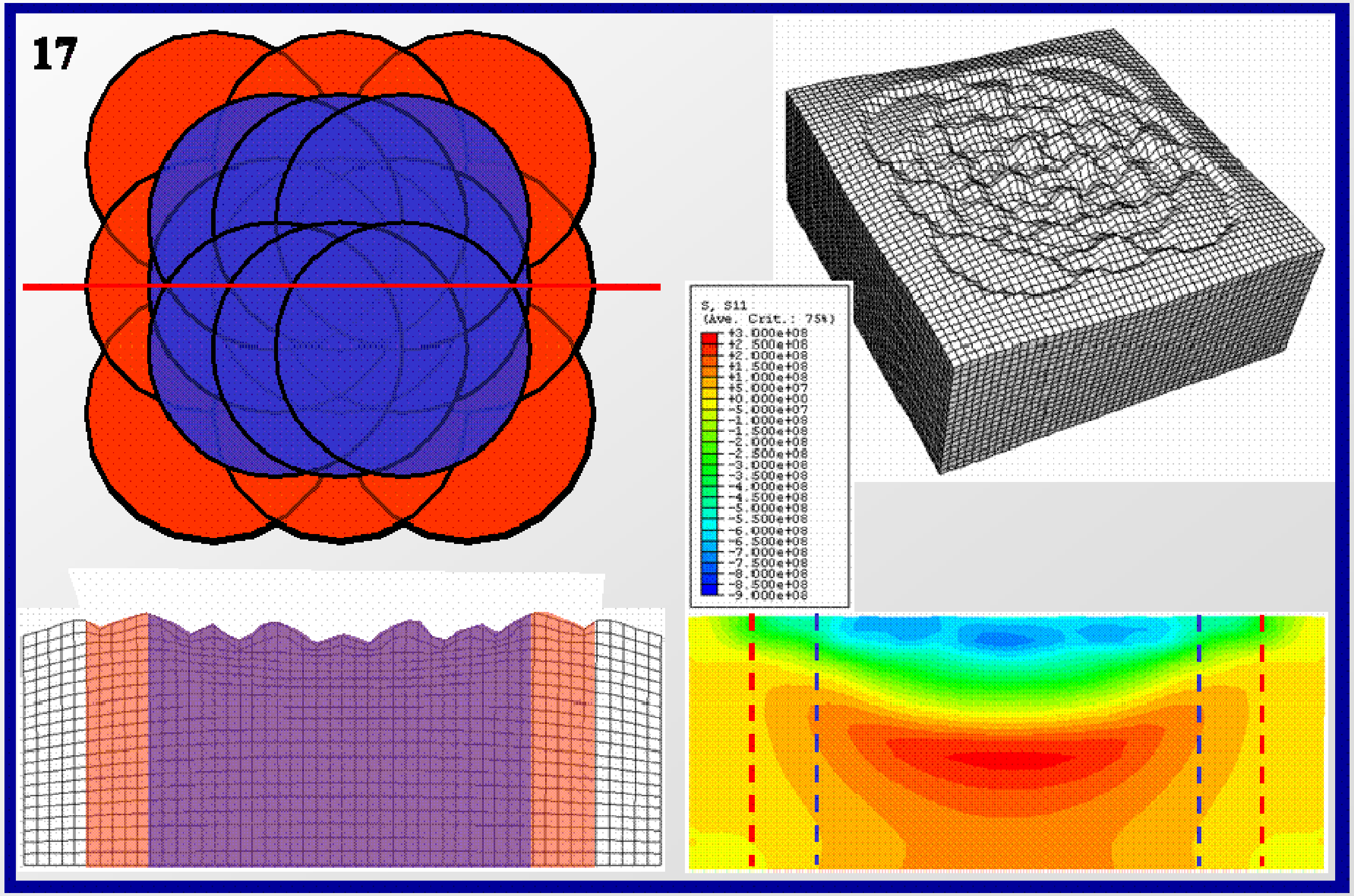

NUMERICAL SIMULATION RESULTS

HARDSHOCK-3D (full scope)

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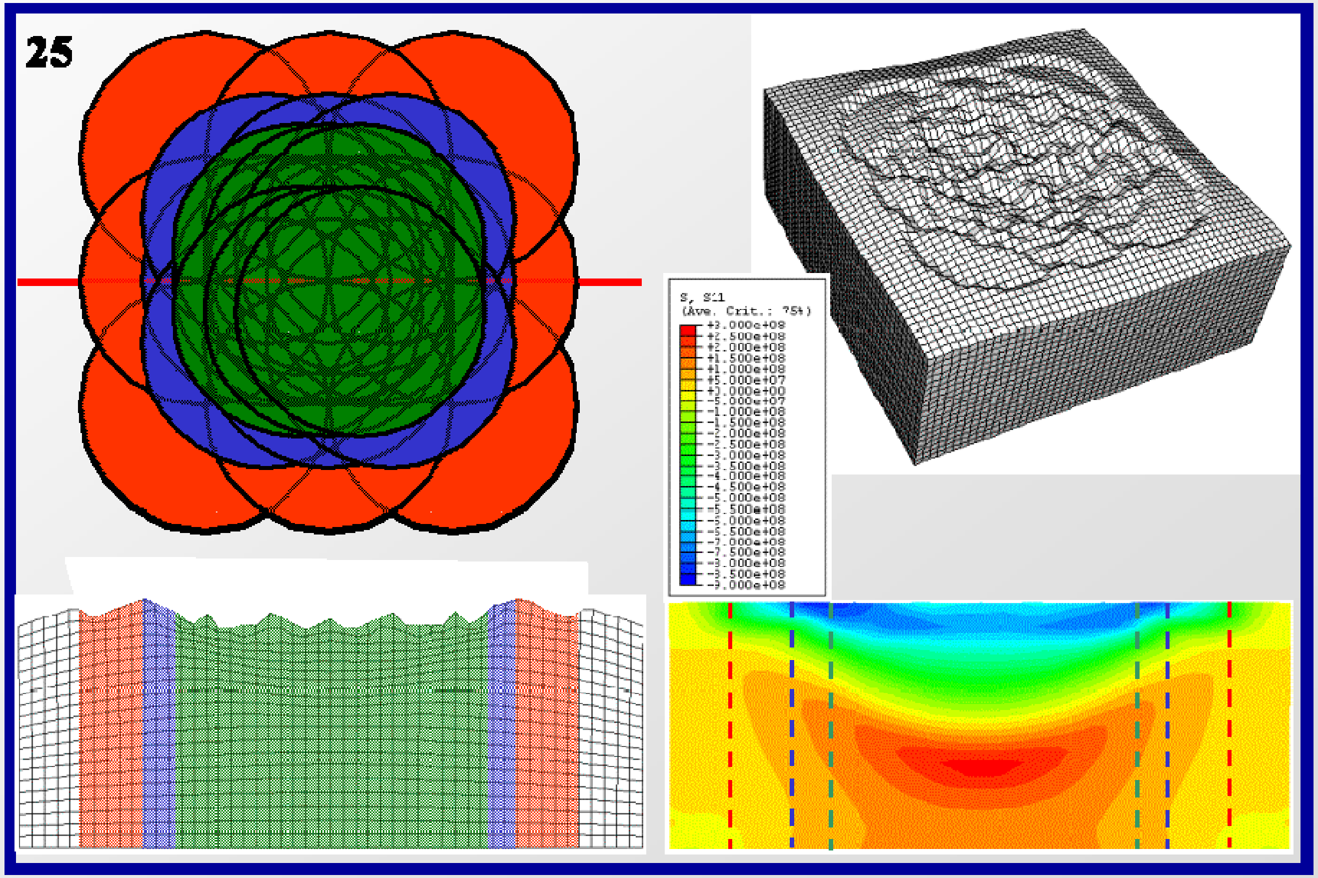


Laser Nd:YAG (λ=1064 nm)

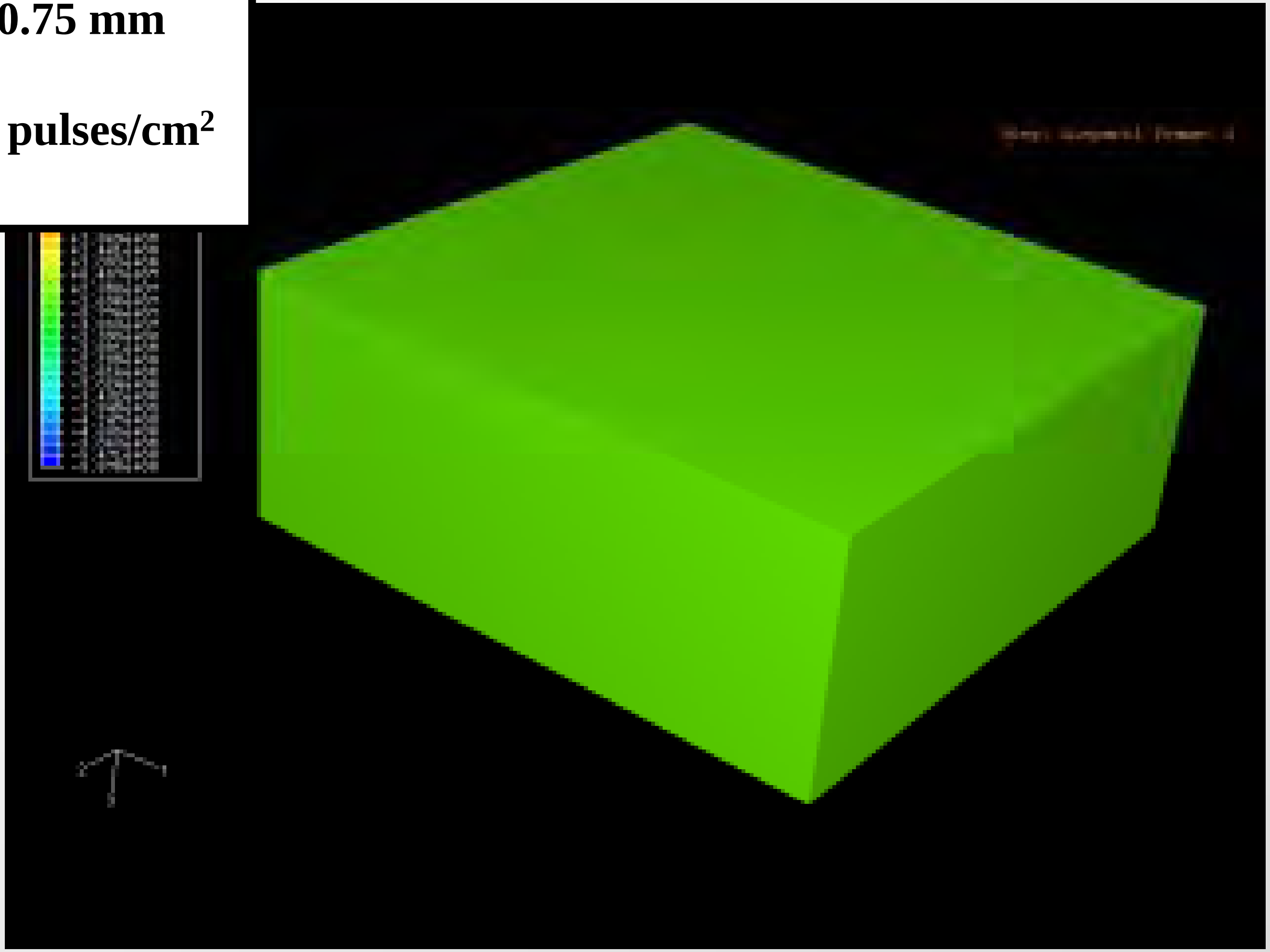
- **Effective Energy 1 J**
- **FWHM 10 ns**
- **Spot radius = 0.75 mm**

Material: Al2024-T3

Spot overlapping 900 pulses/cm^2

α= 0.15

Residual Stress σ_x (Pa)



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Material: Al2024-T3

Spot overlapping 900 pulses/cm^2

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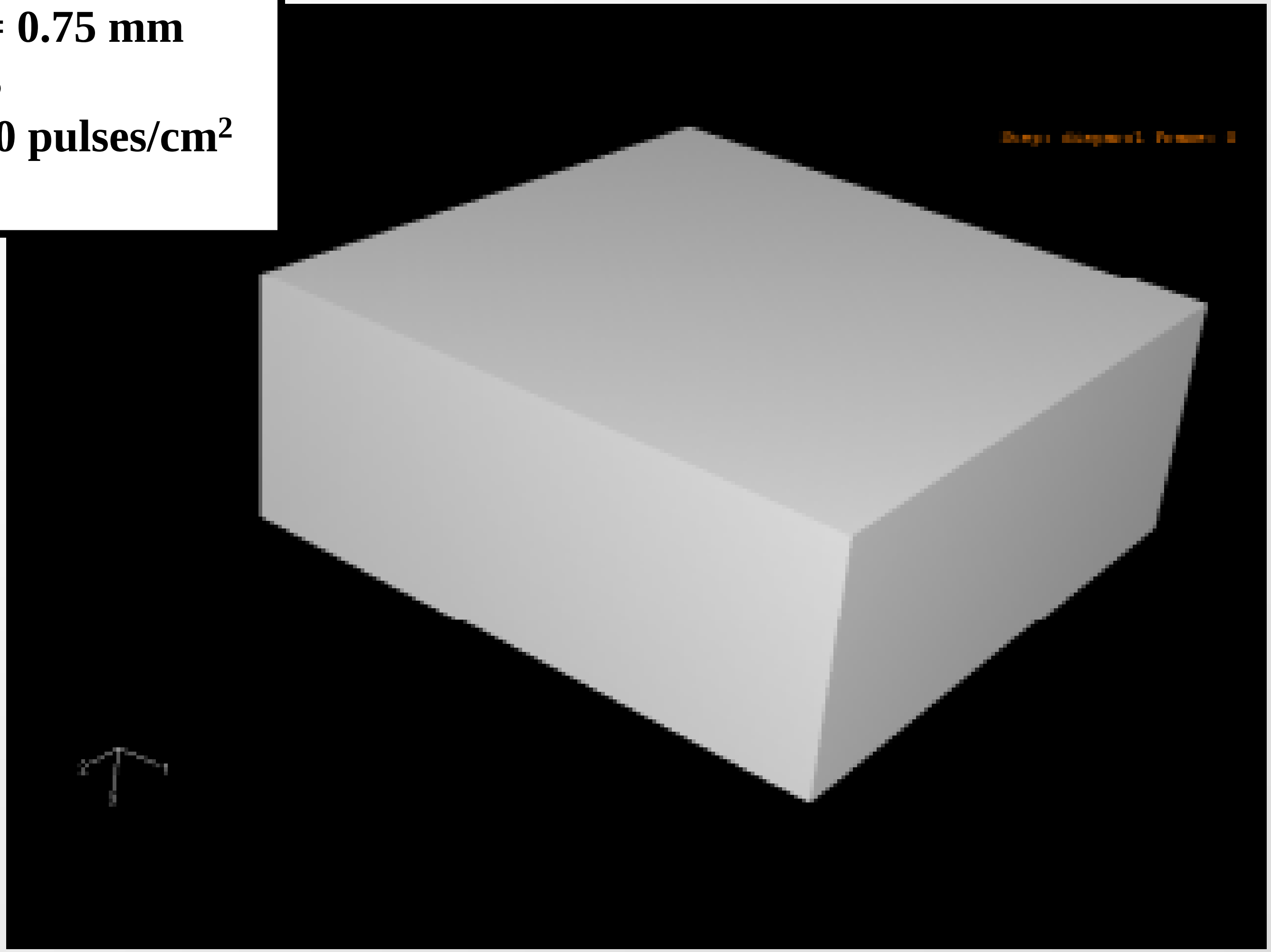
Surface deformation (x 1)



Laser Nd:YAG (λ=1064 nm)

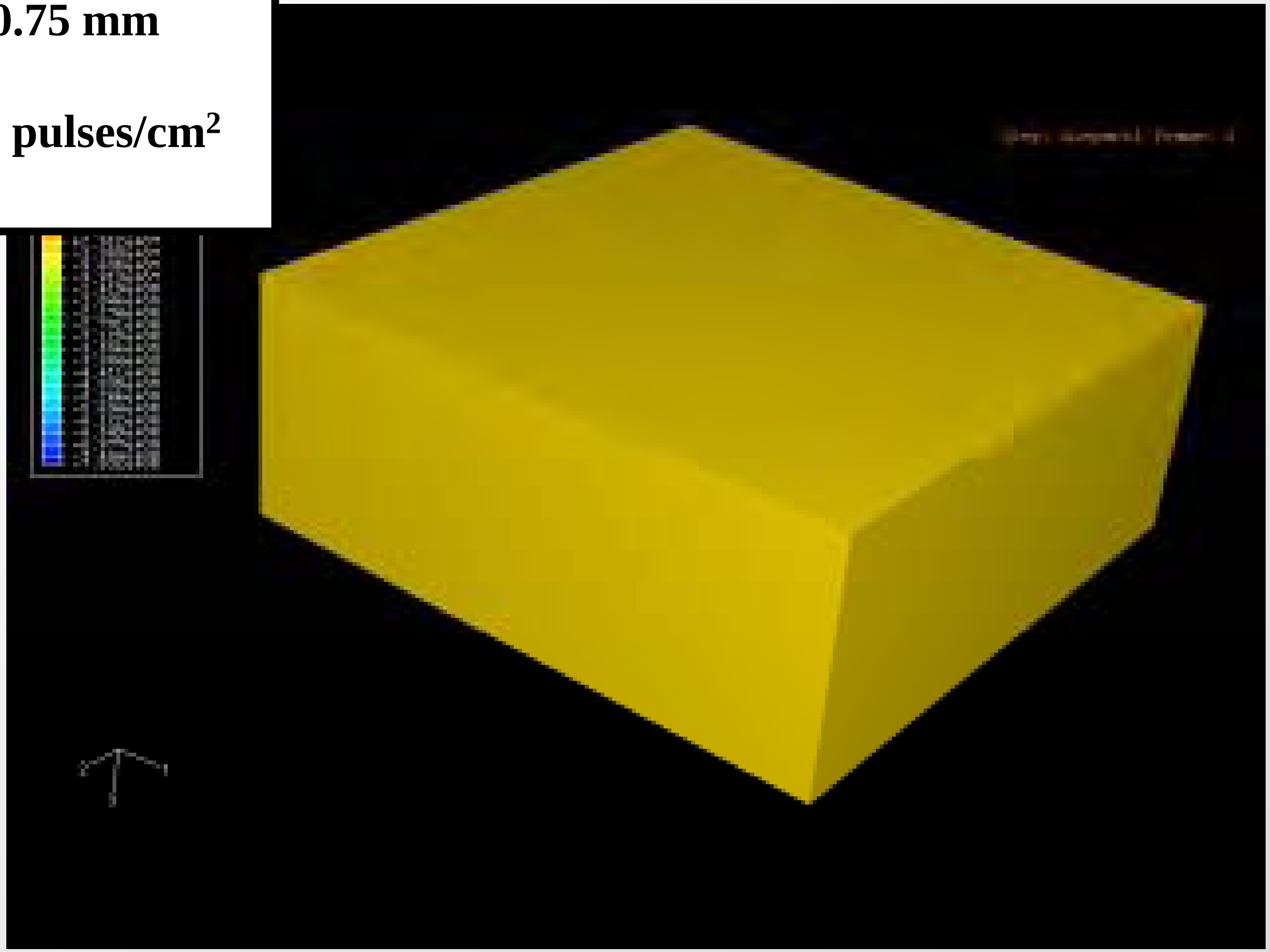
- **Effective Energy 1 J**
- **FWHM 10 ns**
- **Spot radius = 0.75 mm**

Material: Ti-6Al-4V

Spot overlapping 900 pulses/cm^2

α= 0.15

Residual Stress σ_x (Pa)



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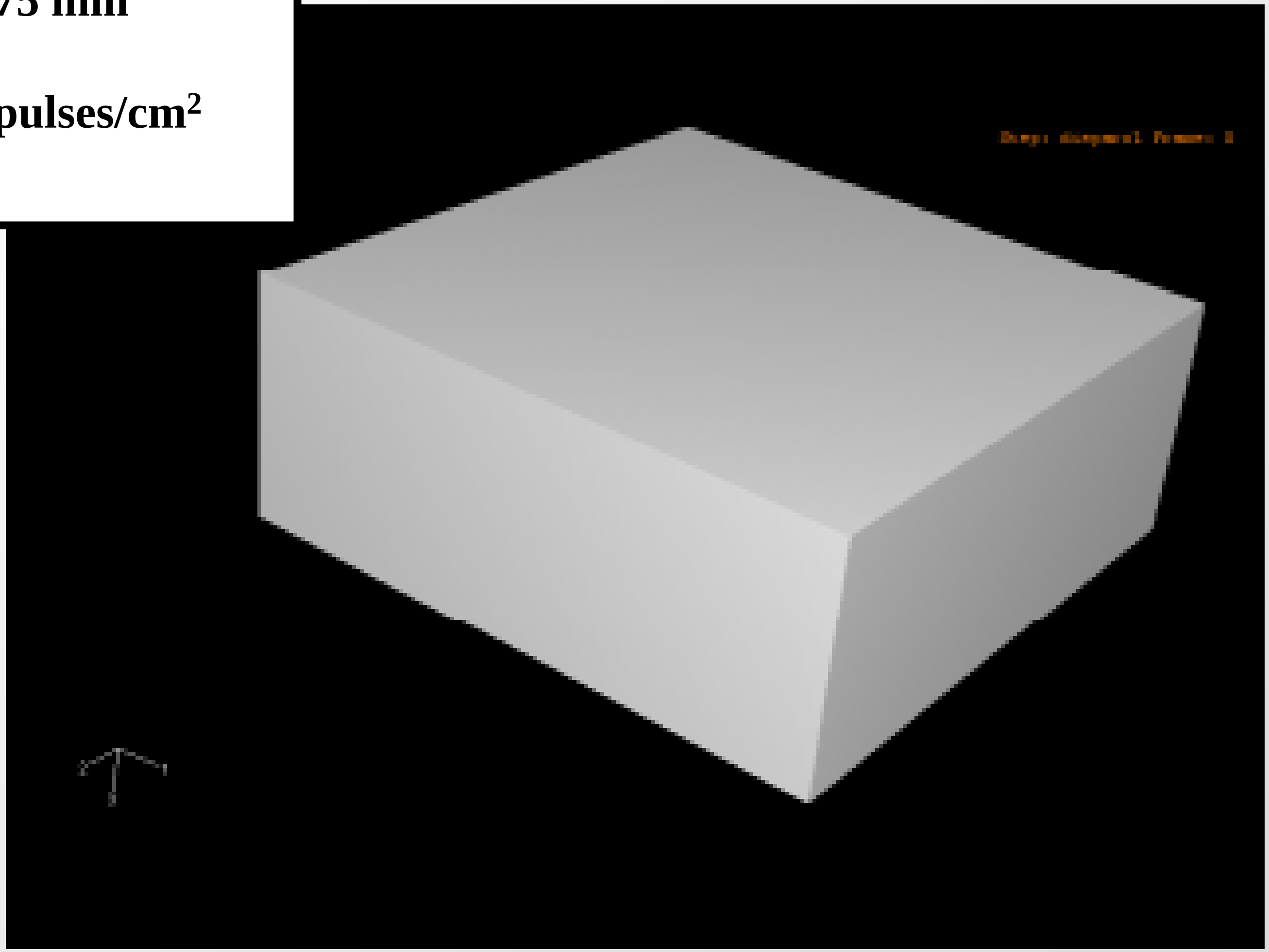
- **FWHM 10 ns**
- **Spot radius = 0.75 mm**

Material: Ti-6Al-4V

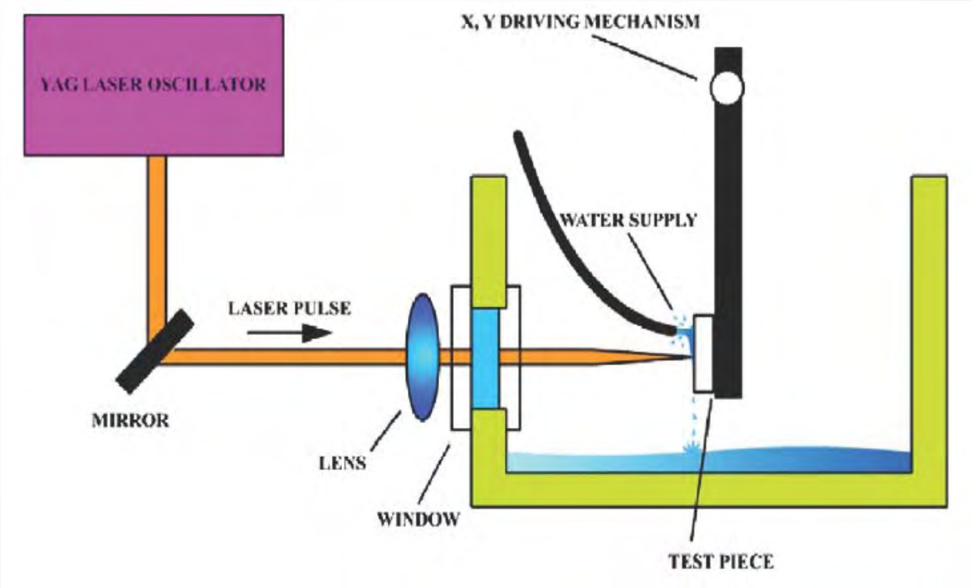
Spot overlapping 900 pulses/cm^2

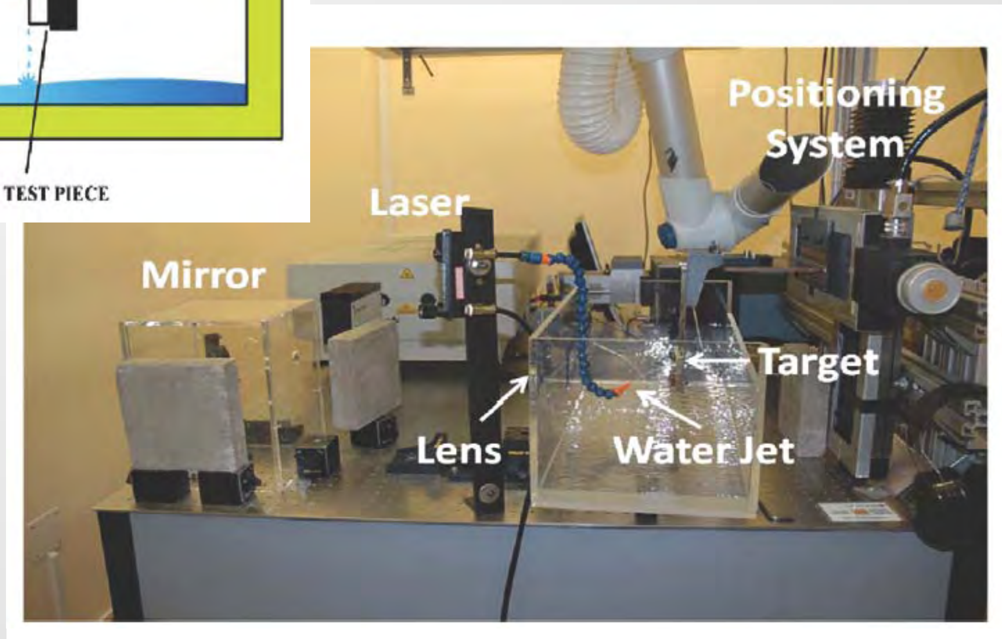
α= 0.15

Surface deformation (x 10)



PROCESS EXPERIMENTAL SETUP



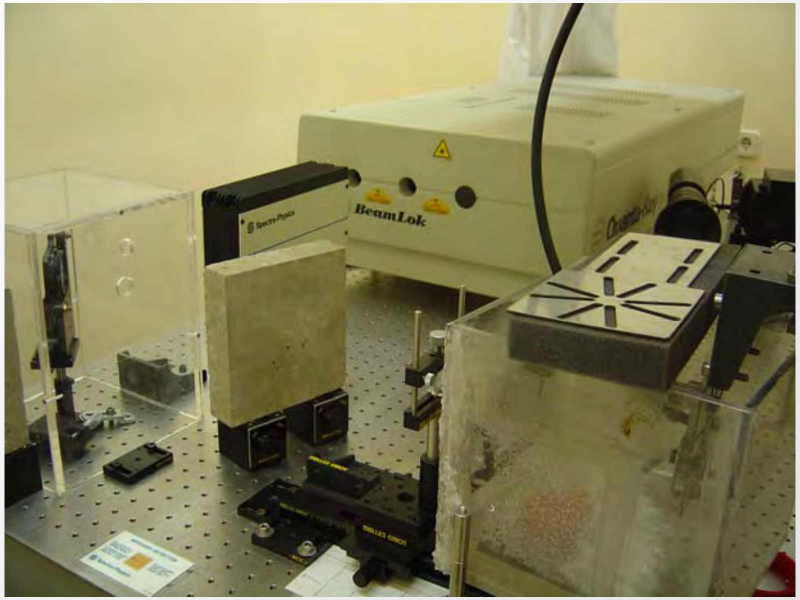


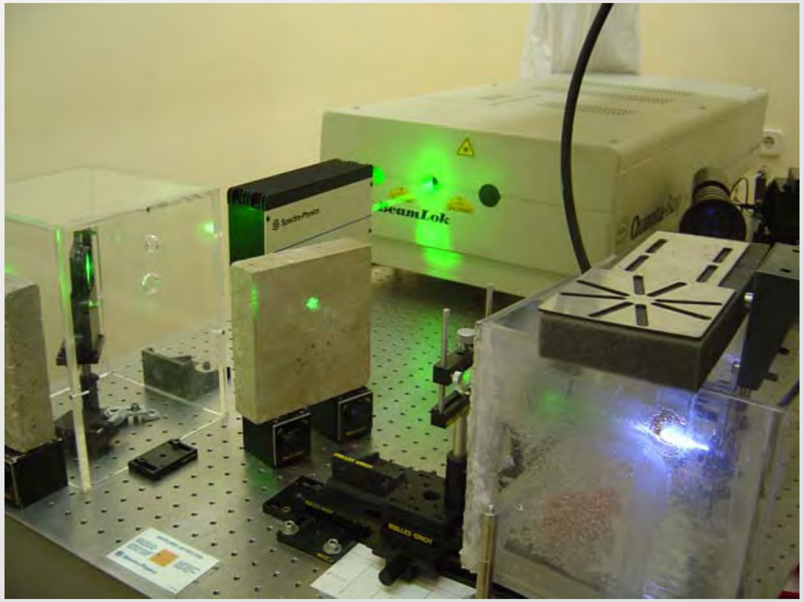
PROCESS EXPERIMENTAL SETUP

Q-SWITCHED Nd:YAG LASER

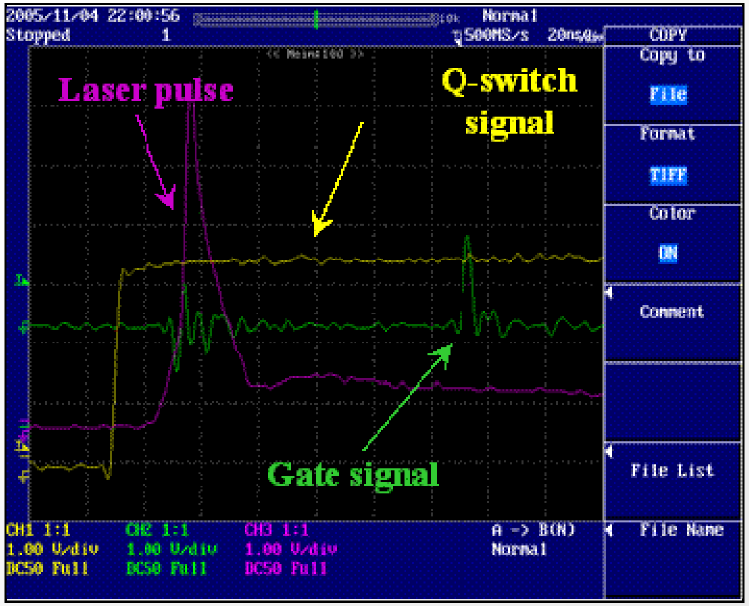
$$\begin{cases} \lambda = 1064\,\mathrm{nm};\ E = 2{,}5\ \mathrm{J/pulse} \\ \lambda = 532\,\mathrm{nm};\ \ E = 1{,}4\ \mathrm{J/pulse} \end{cases}$$

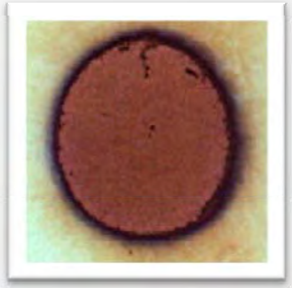
τ = 10 ns; f = 10 Hz

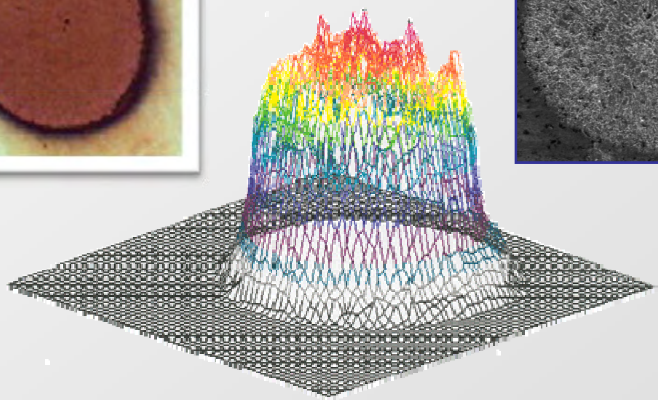


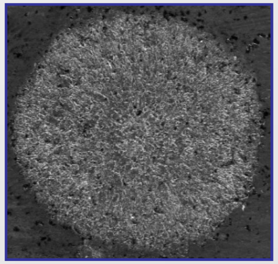


PROCESS EXPERIMENTAL SETUP







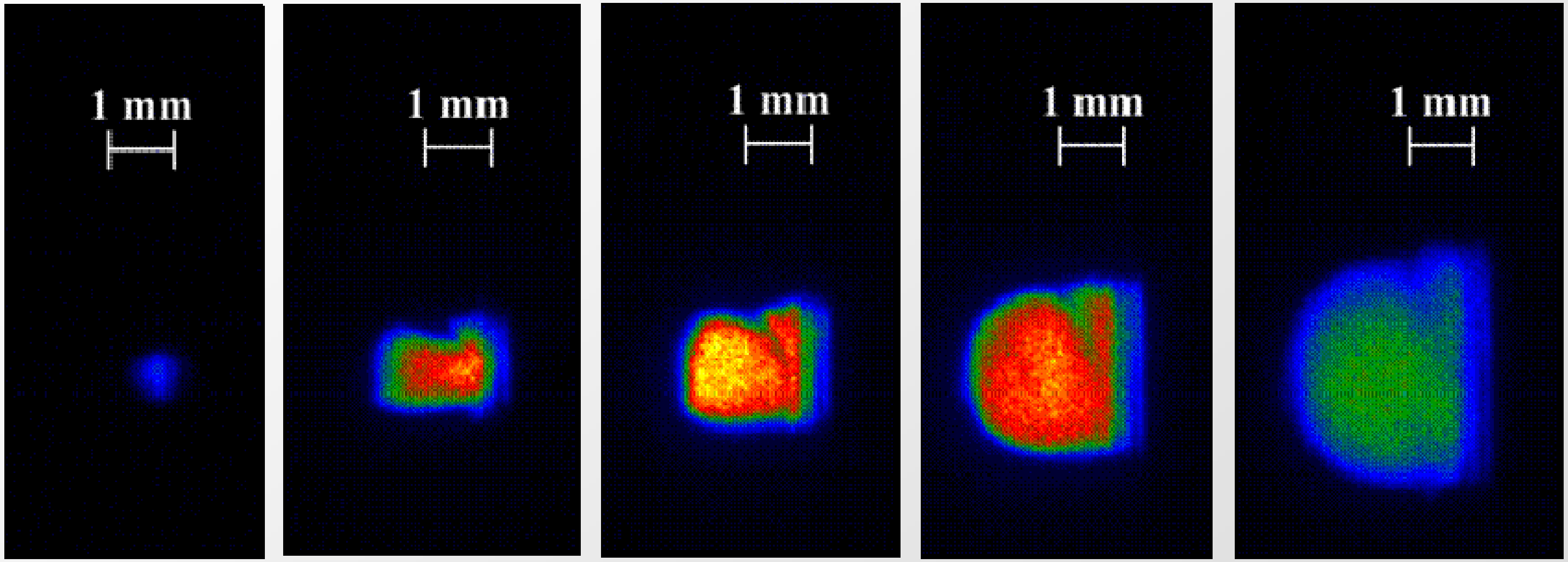


LSP TREATMENT PARAMETERS	
Laser wavelength (nm) ; Q-switched Nd:YAG	1064
Energy per pulse (J/pulse)	2,0
Pulse temporal width (ns)	≈ 9
Laser spot diameter (mm)	1.5
Ratio x-y pitch	1
Confining medium	Water jet ≈ 2 bar
Absorbing coating overlay	No

PROCESS EXPERIMENTAL SETUP

EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

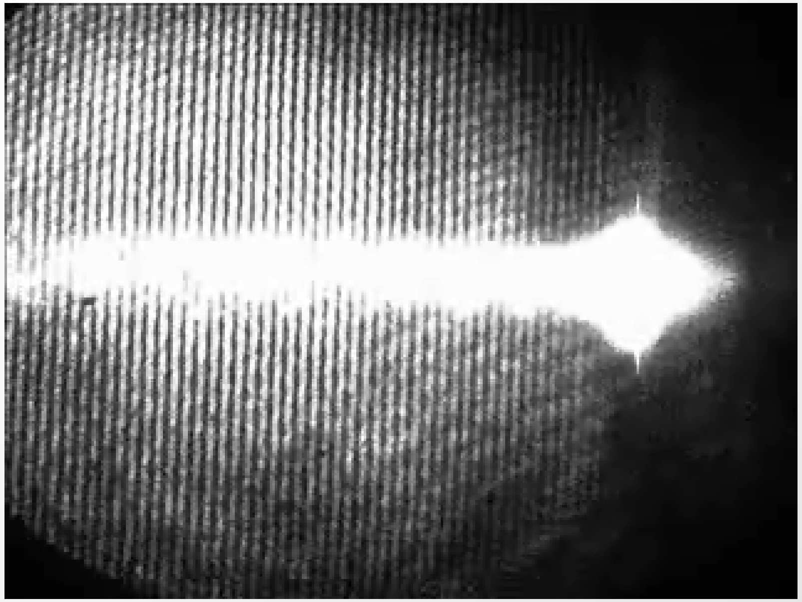
DIRECT IMAGING - HYDRODYNAMIC ANALYSIS

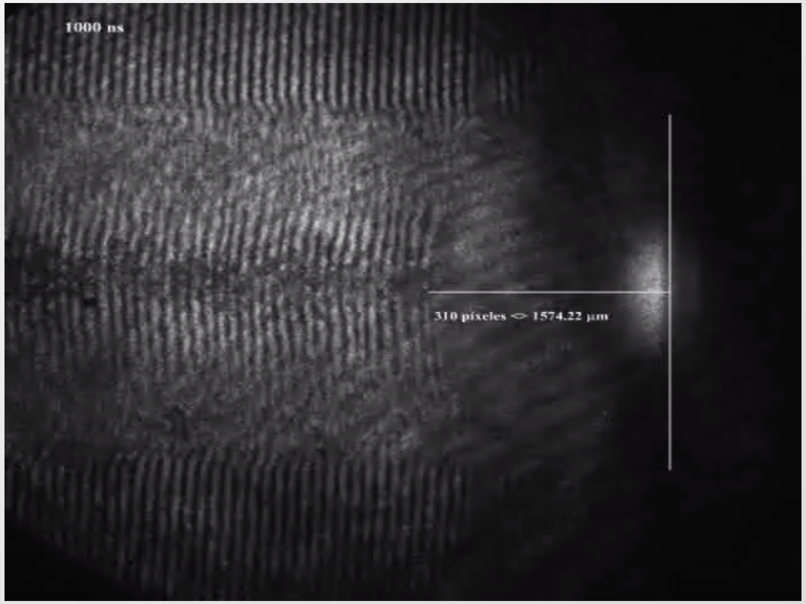


t = 10 ns | t = 25 ns | t = 50 ns | t =100 ns | t =200 ns

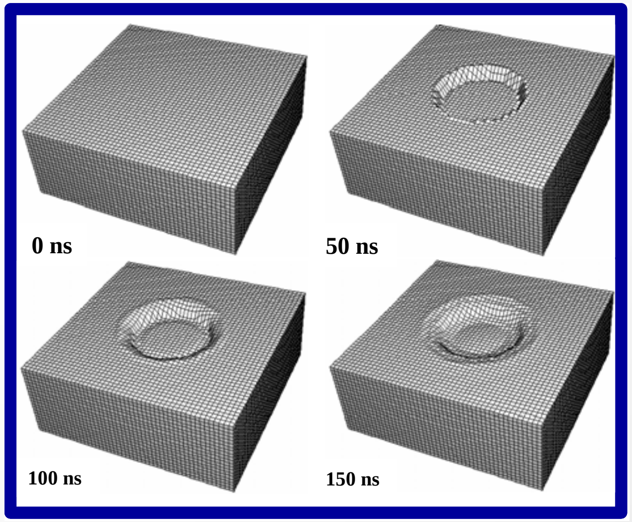
EXPERIMENTAL VALIDATION. DIAGNOSIS SETUP

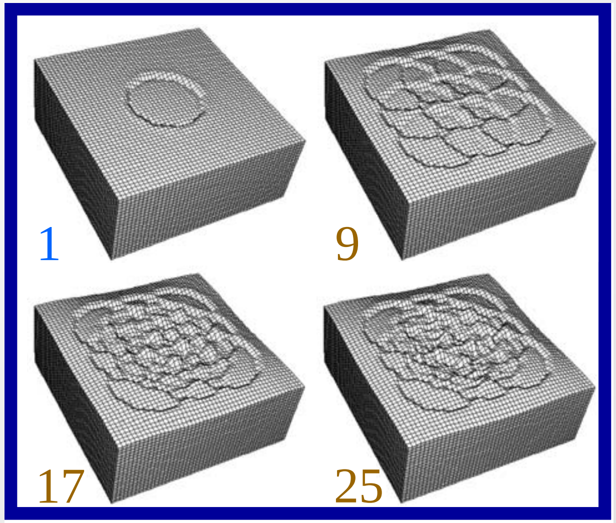
IMAGING TECHNIQUES – SCHLIEREN / INTERFEROMETRY

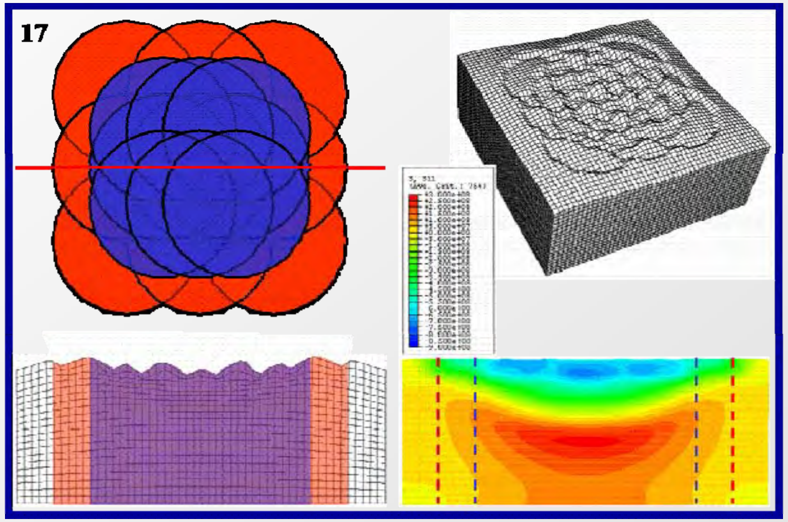


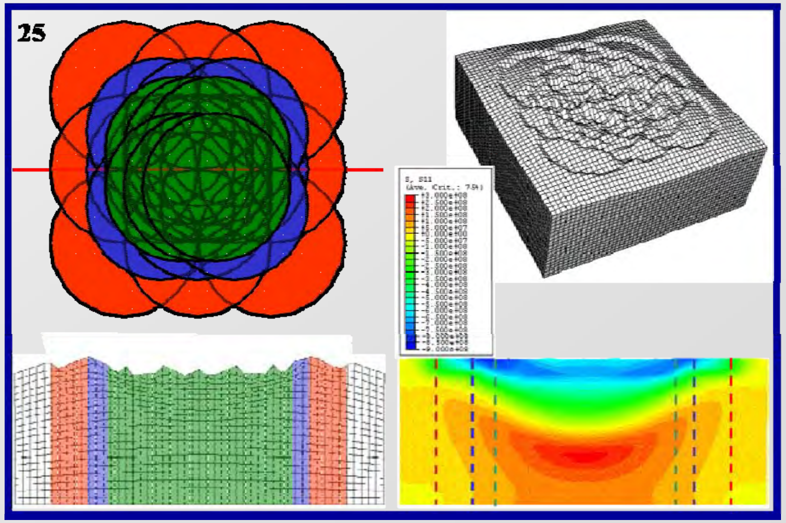


EXPERIMENTAL PROCEDURE









EXPERIMENTAL PROCEDURE

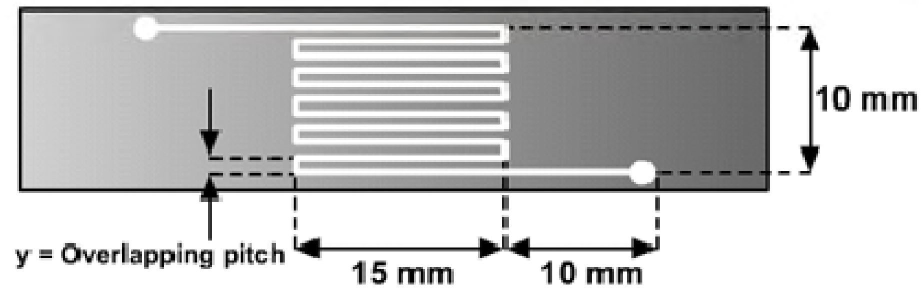


Table I: Relation between overlapping pitch and equivalent number of pulses per unit surface corresponding to the defined sweeping procedure.

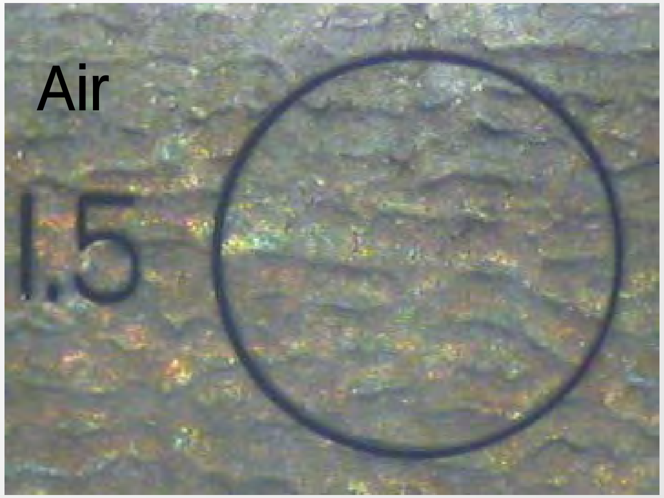
Overlapping pitch Y (mm)	Equivalent overlapping density (pulses/cm^2)
0.588	289
0,33	900
0.285	1225
0.2	2500
0,141	5000

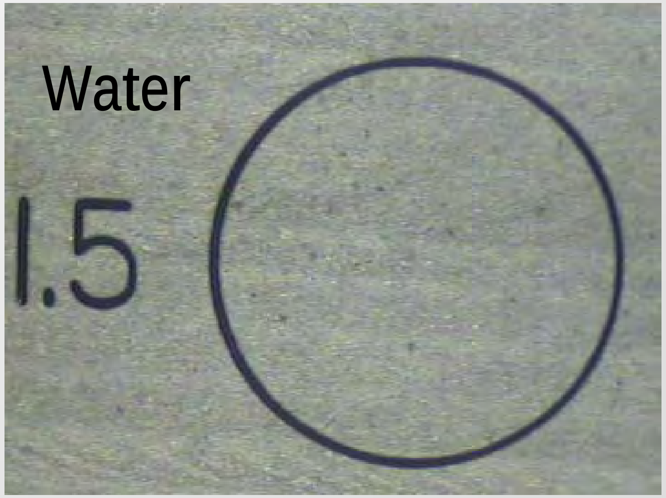
EXPERIMENTAL RESULTS

Material: Al2024 T3

Pulses: ∅=1,5 mm; τ=10 ns; f=10 Hz;
E=1 J/pulse; I=1,41 GW/cm^2

Swept Area : 15x15 mm^2; 2500 pulses/cm^2



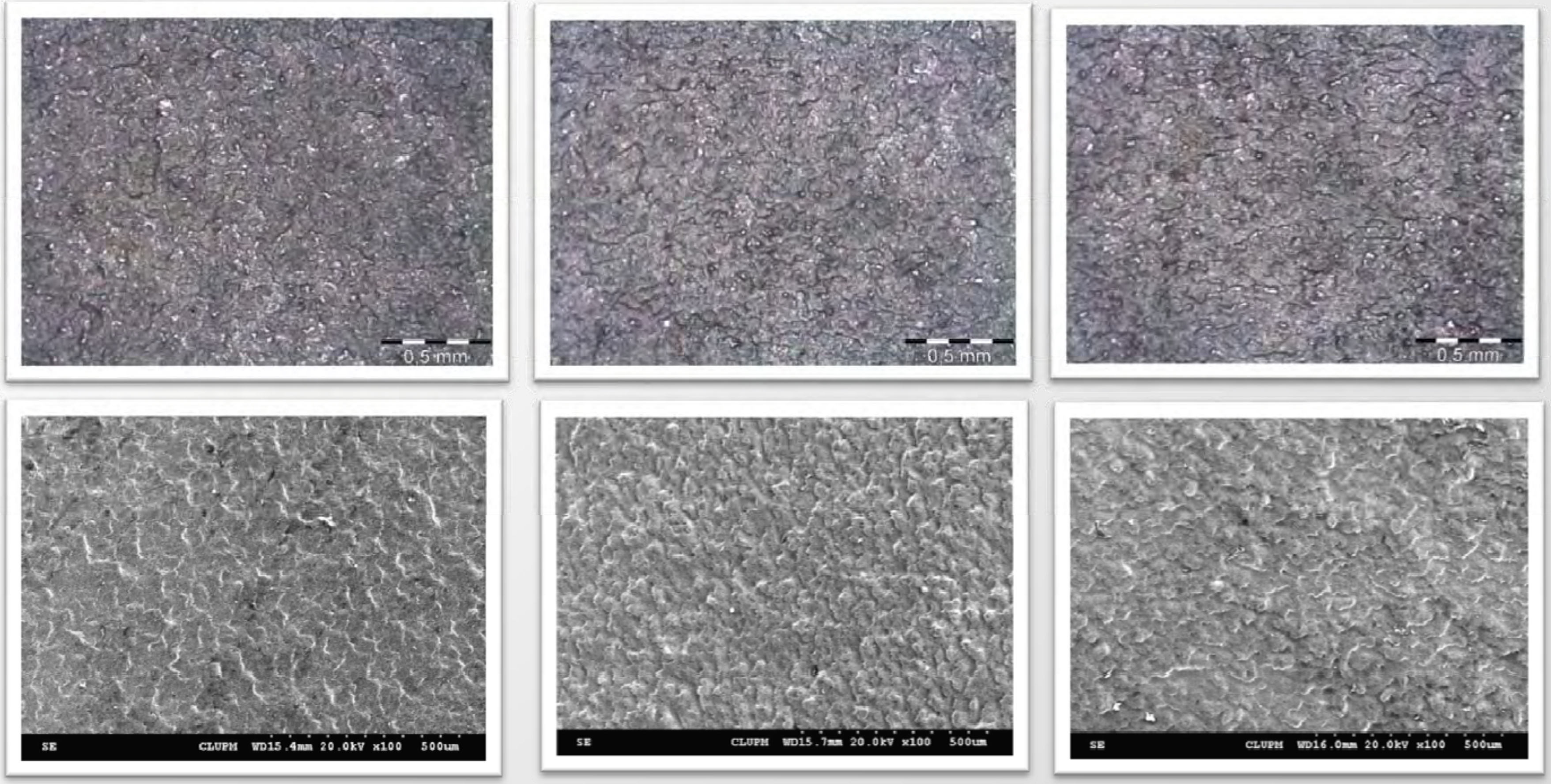


Reported Analysis

	Al2024-T351 30x20x8 mm^3	Ti6Al4V 30x20x10 mm^3
900 pulses/cm^2		
1600 pulses/cm^2		
2500 pulses/cm^2		
5000 pulses/cm^2		

EXPERIMENTAL RESULTS

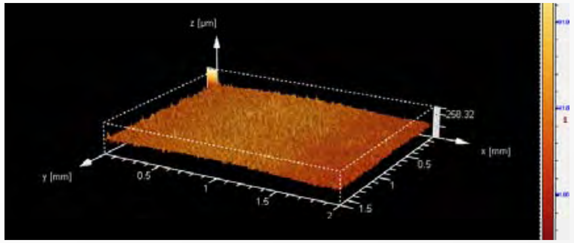
Surface Roughness (Microscopy): Al2024-T351

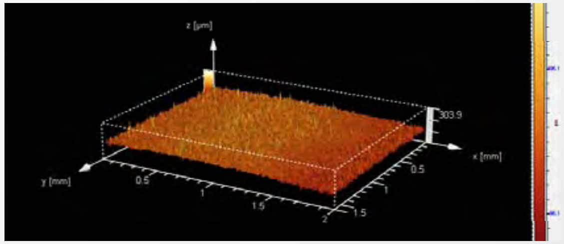


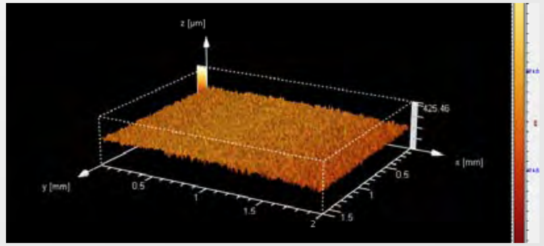
900 pulses/cm² — **1600 pulses/cm²** — **2500 pulses/cm²**

EXPERIMENTAL RESULTS

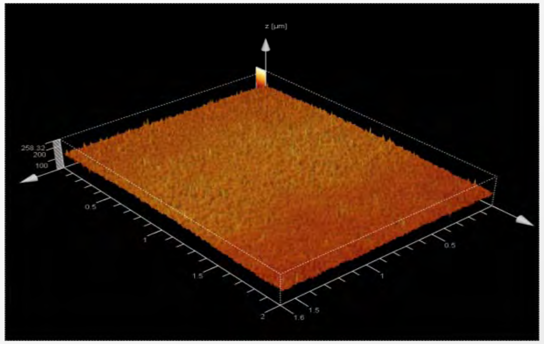
Surface Roughness (Topographic Confocal microscopy): Al2024-T351

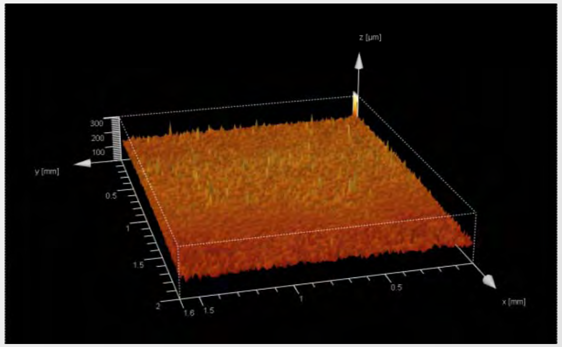


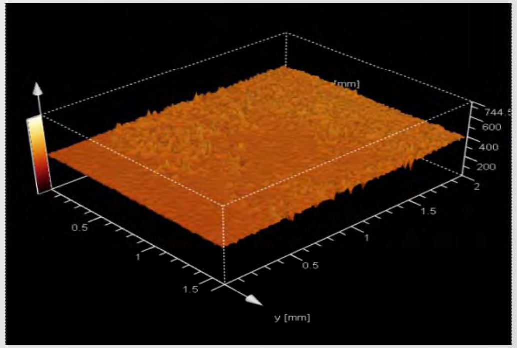




900 pulses/cm^2 **1600 pulses/cm^2** **2500 pulses/cm^2**



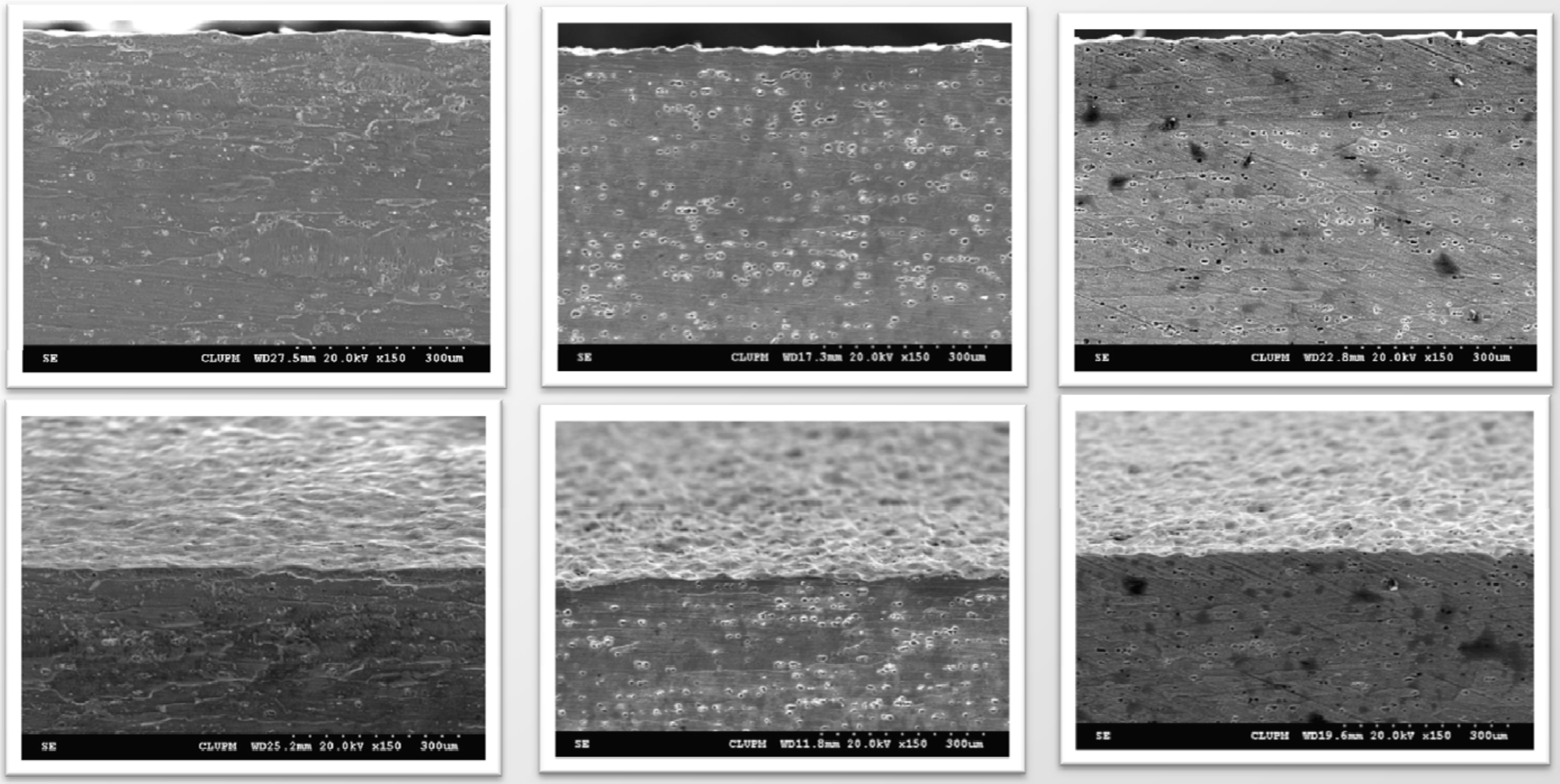




	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (μm)	7.96	5.23	4.82	4.96
<Δz>	----	10.30	20.00	26.82

EXPERIMENTAL RESULTS

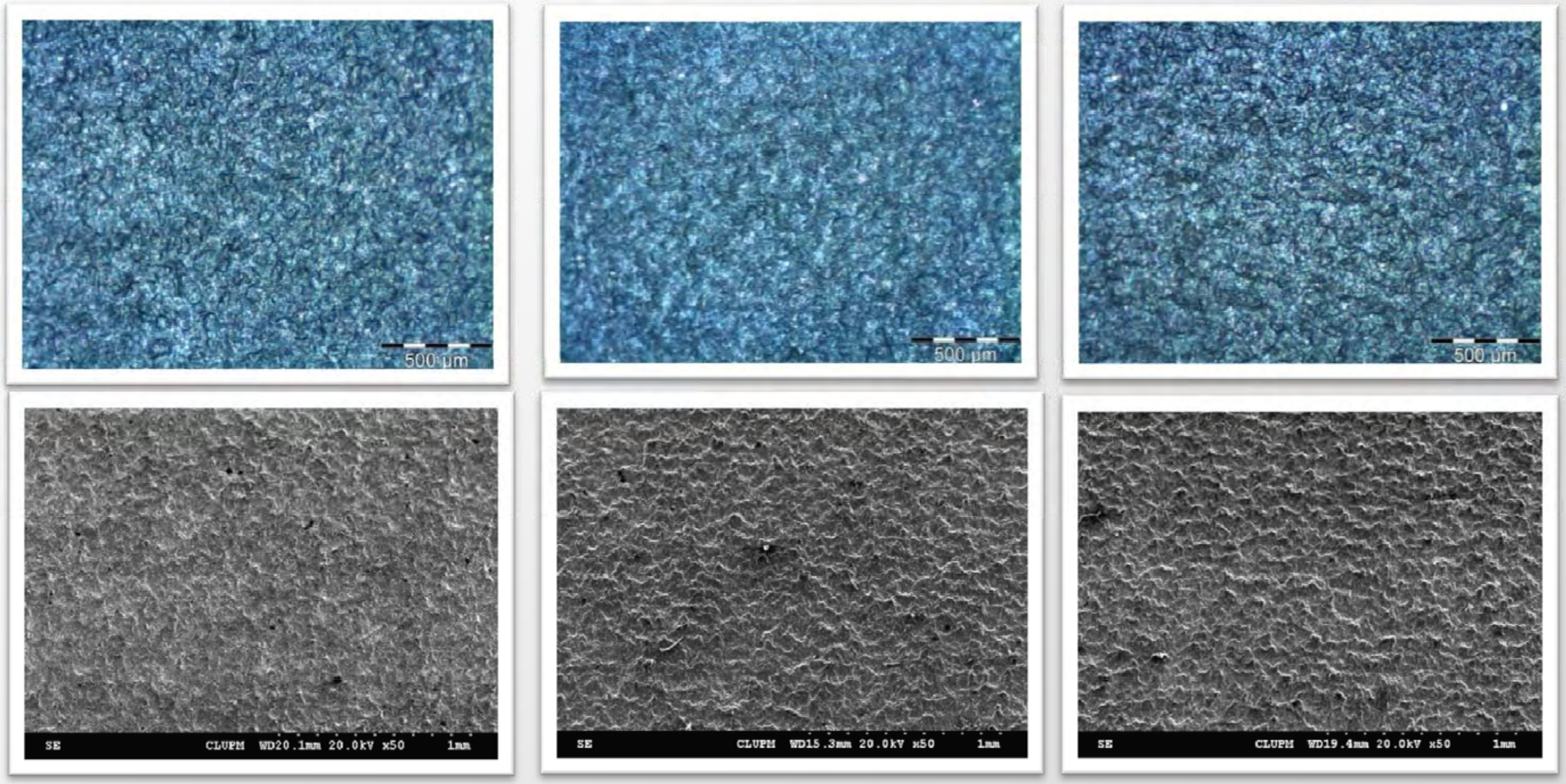
Microscopic material compactation: Al2024-T351



900 pulses/cm^2 | **1600 pulses/cm^2** | **2500 pulses/cm^2**

EXPERIMENTAL RESULTS

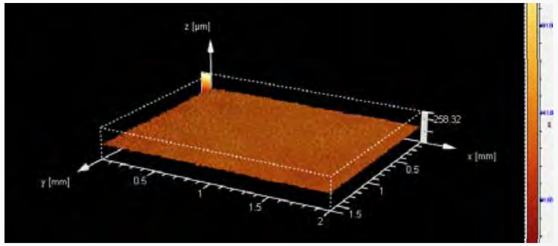
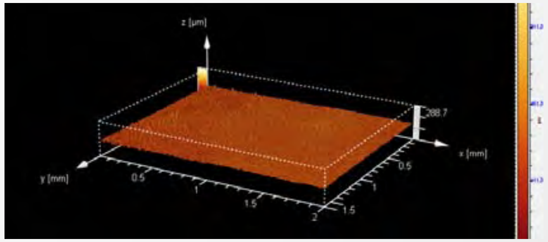
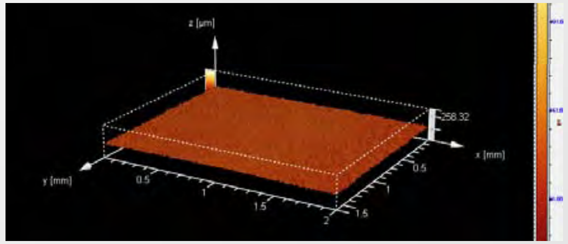
Surface Roughness (Microscopy): Ti6Al4V



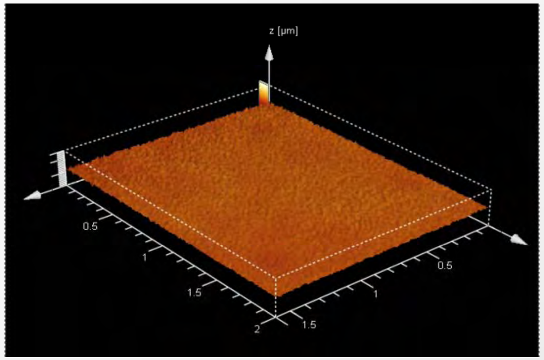
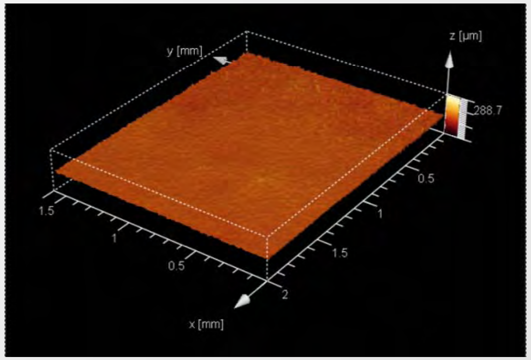
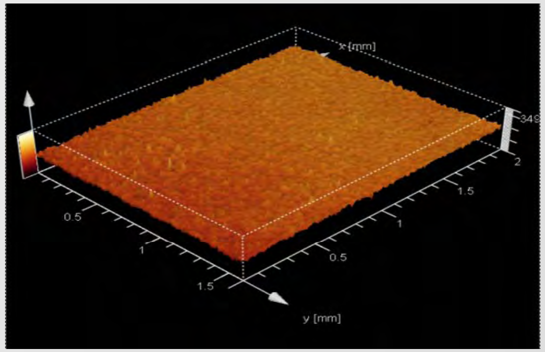
900 pulses/cm² | **2500 pulses/cm²** | **5000 pulses/cm²**

EXPERIMENTAL RESULTS

Surface Roughness (Topographic Confocal microscopy): Ti6Al4V

900 pulses/cm^2 | 2500 pulses/cm^2 | 5000 pulses/cm^2

	No treatment	900 pulses/cm^2	1600 pulses/cm^2	2500 pulses/cm^2
Pa (μm)	9.98	3.62	3.87	3.87
<Δz>	----	2.81	7.40	5.80

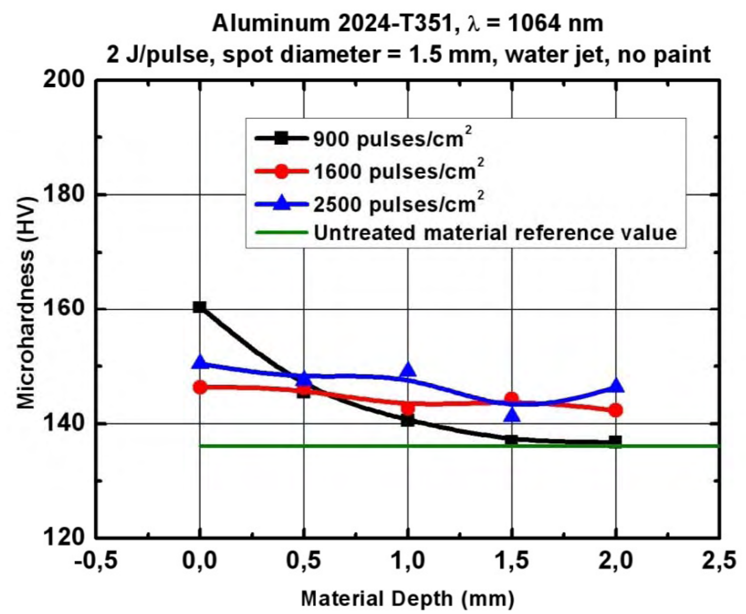
EXPERIMENTAL RESULTS

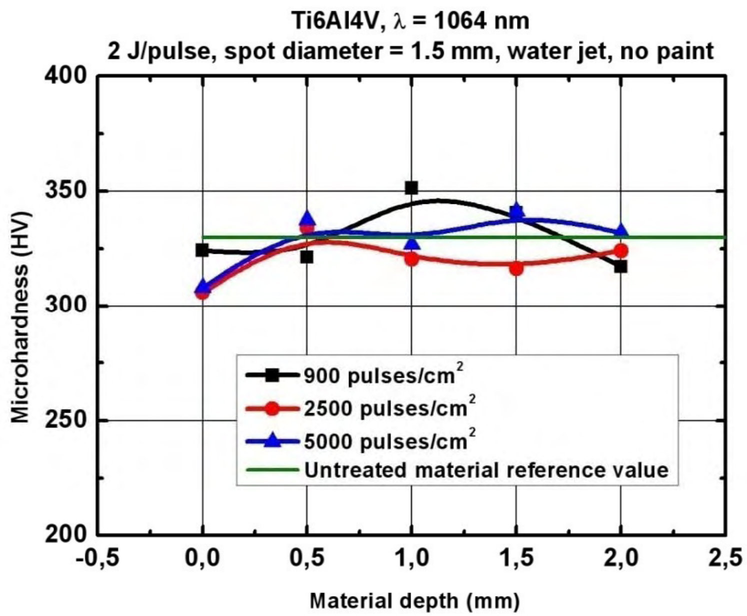
Microscopic material compactation: Ti6Al4V

900 pulses/cm^2 | **2500 pulses/cm^2** | **5000 pulses/cm^2**

EXPERIMENTAL RESULTS

Microhardness (HV)





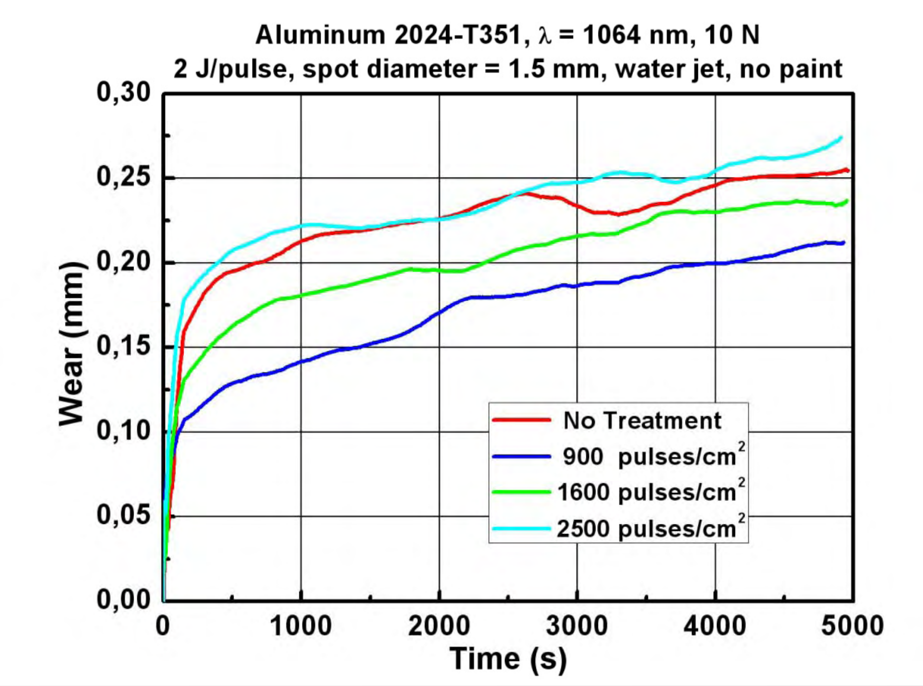
Slight increase in microhardness in Al2024-T351
Higher for higher LSP treatement intensity

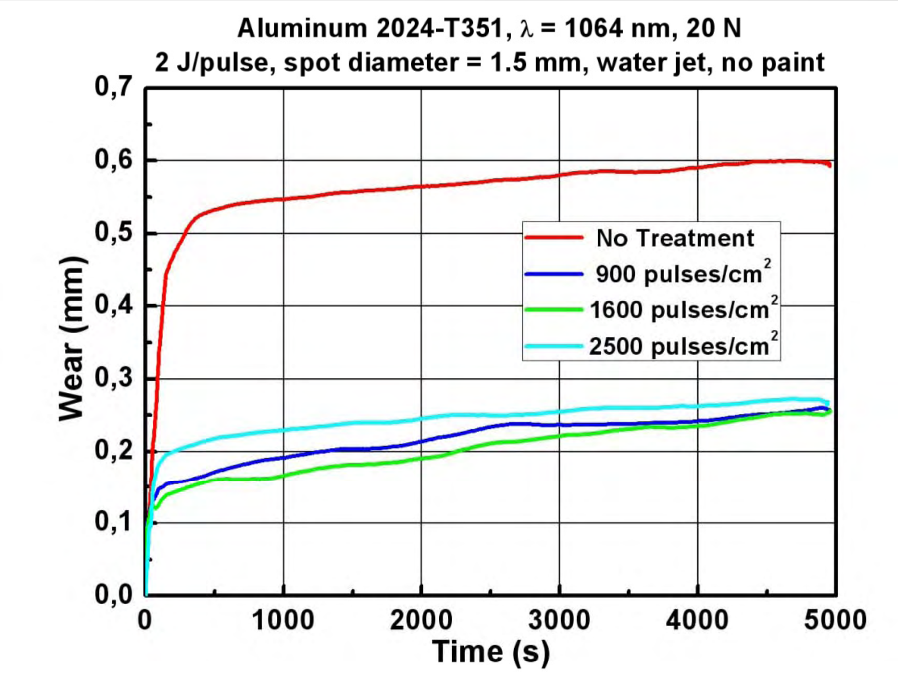
No apparent hardening effect in Ti6Al4V.

EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Al2024-T351





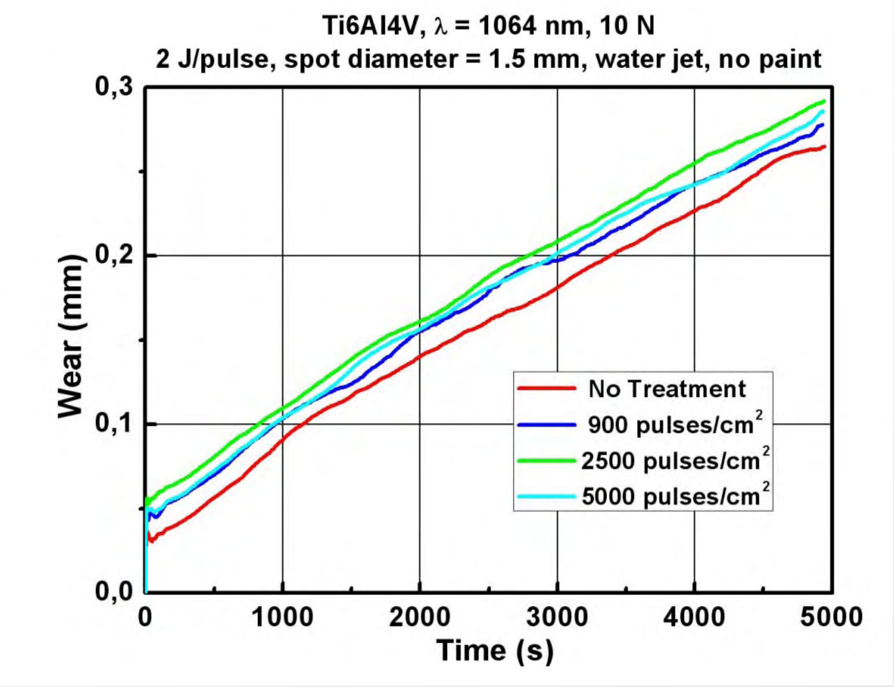
Slight wear improvement in Al2024-T351 at low loads

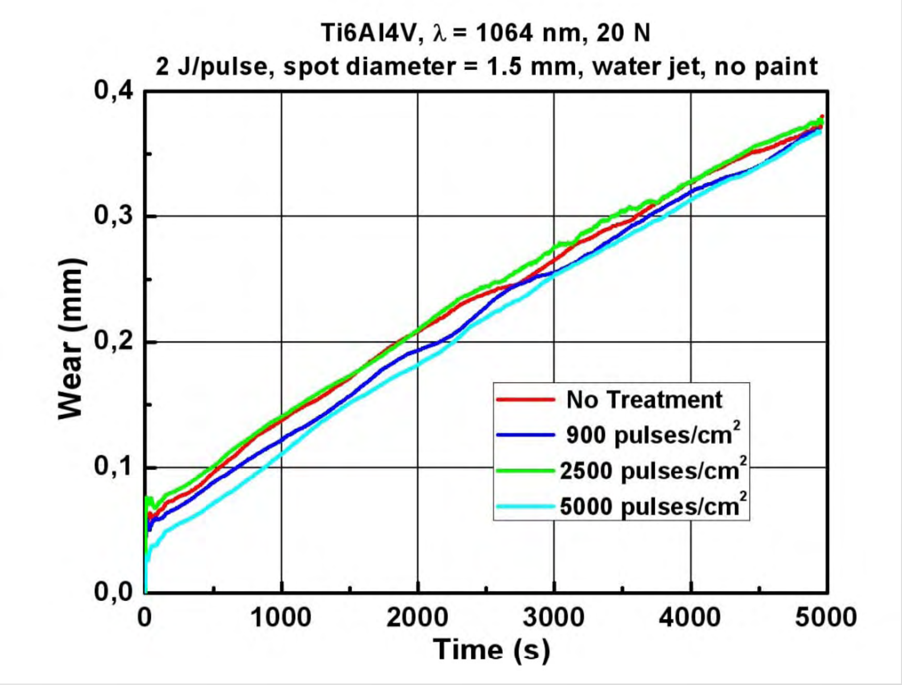
Considerable wear improvement in Al2024-T351 at moderate loads

EXPERIMENTAL RESULTS

Wear resistance (According to ASTM G99-04)

Ti6Al4V





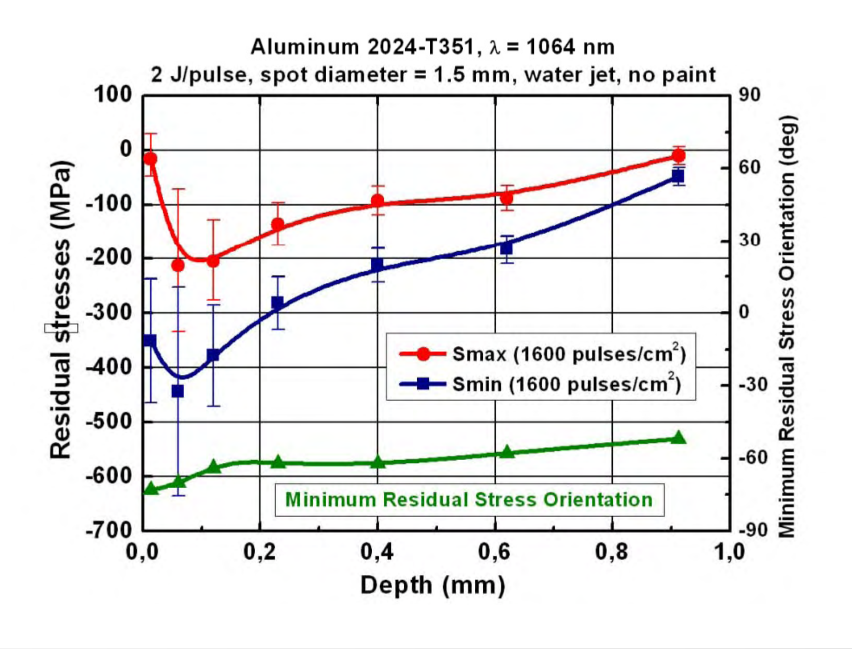
Slight negative wear impact in Ti6Al4V at low loads

Inappreciable wear improvement in Ti6Al4V at moderate loads

EXPERIMENTAL RESULTS

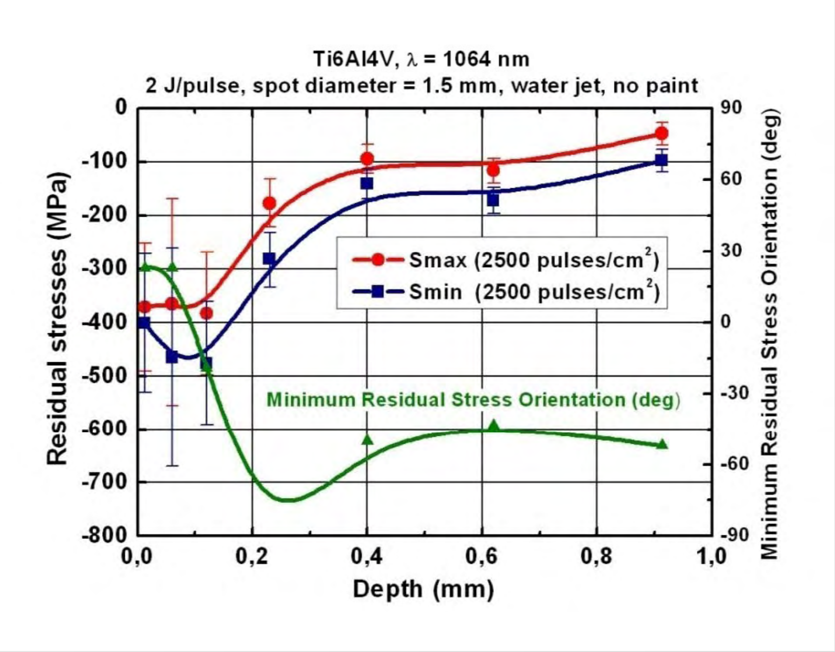
Residual Stresses (According to ASTM E837-08)

Al2024-T351



Relatively broad difference between S_{max} and S_{min} in Al2024-T351

Ti6Al4V

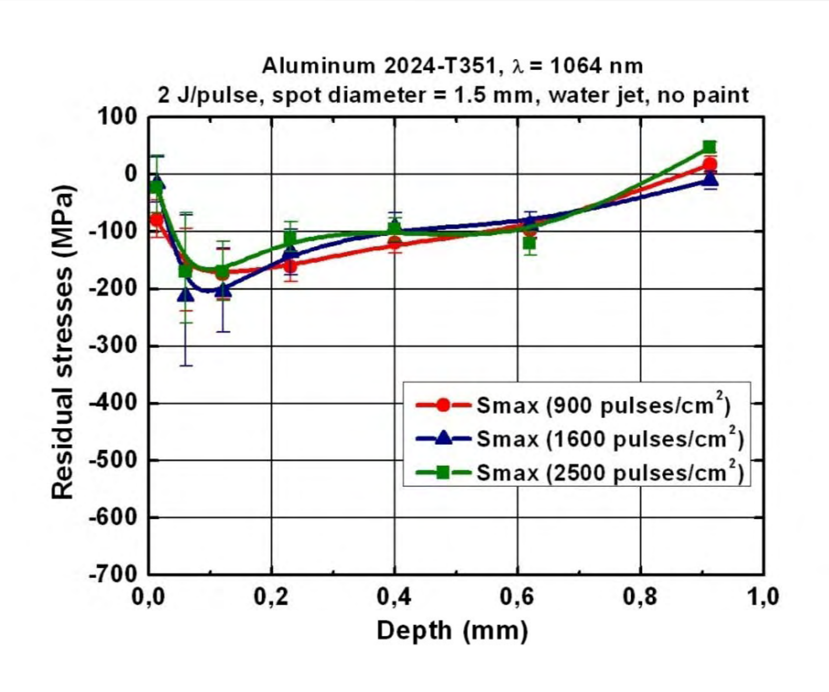


Relatively small difference between S_{max} and S_{min} in Ti6Al4V

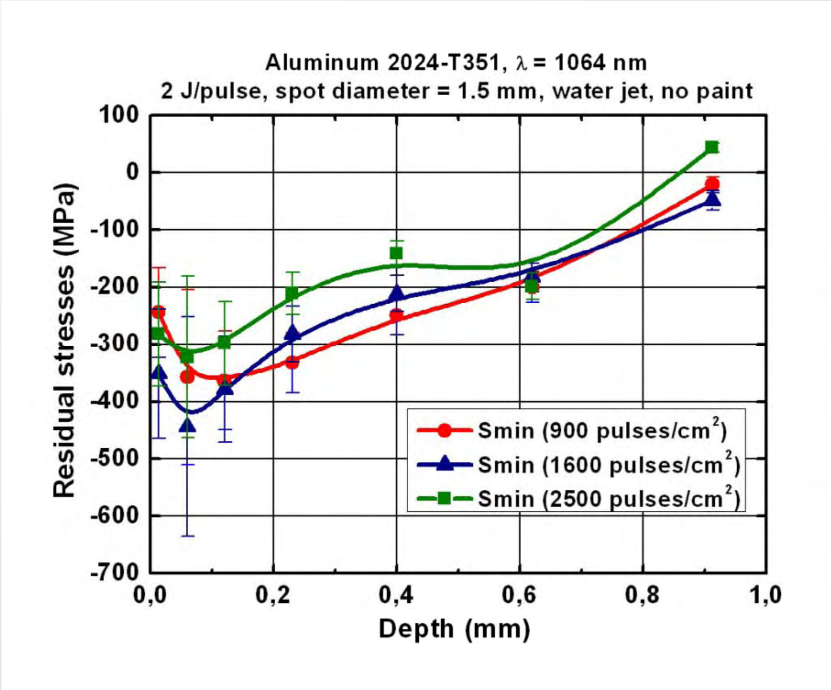
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Al2024-T351



S_{max} in Al2024-T351 for different irradiation intensities

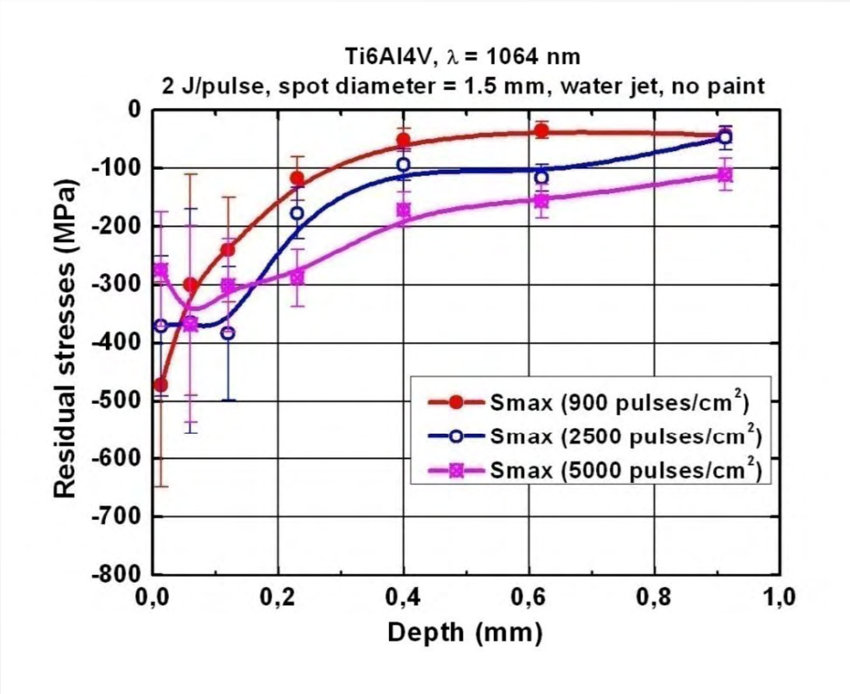


S_{min} in Al2024-T351 for different irradiation intensities

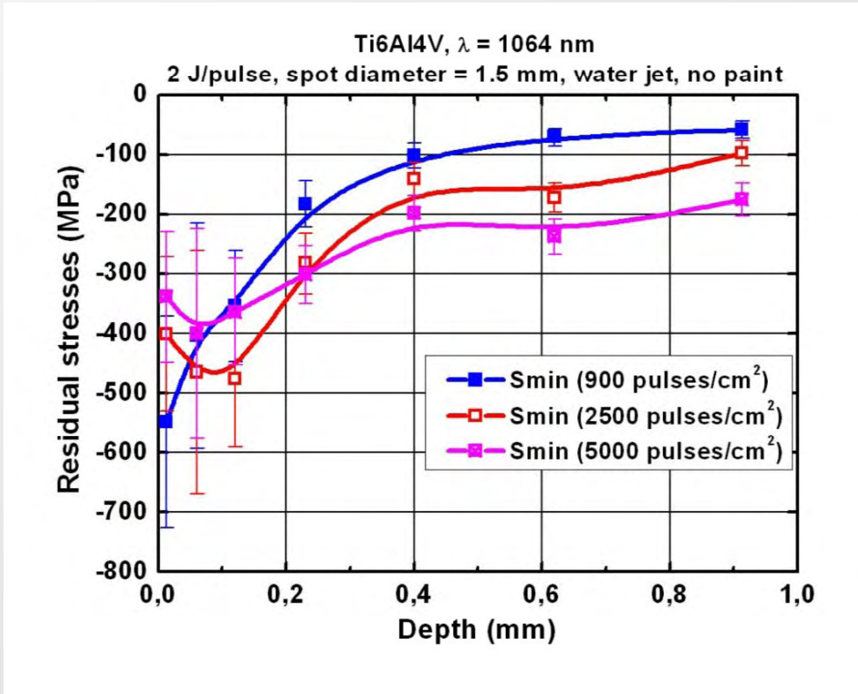
EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V

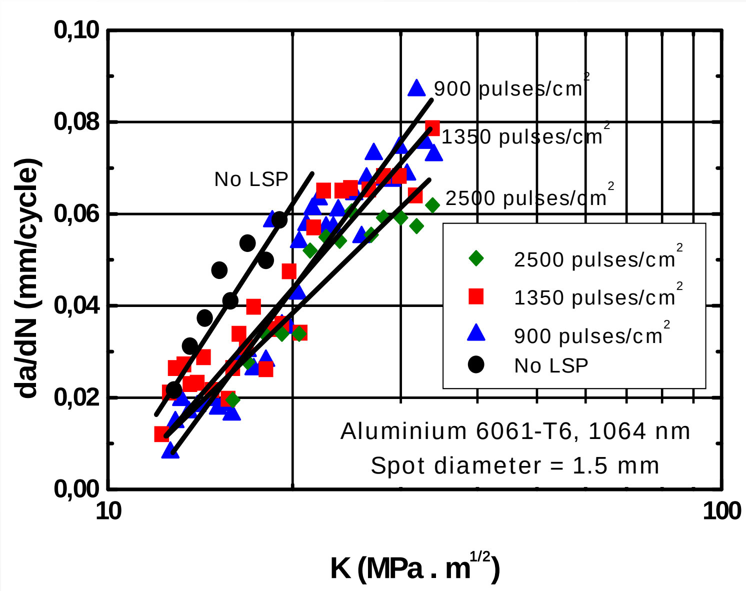


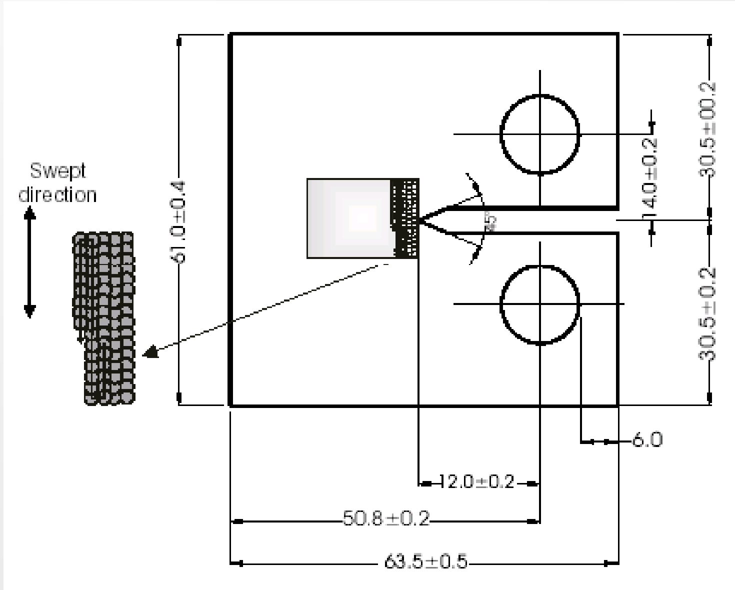
S_{max} in Ti6Al4V for different irradiation intensities



S_{min} in Al2024-T351 for different irradiation intensities

EXPERIMENTAL RESULTS





$$\frac{da}{dN} = C.K^{m}$$

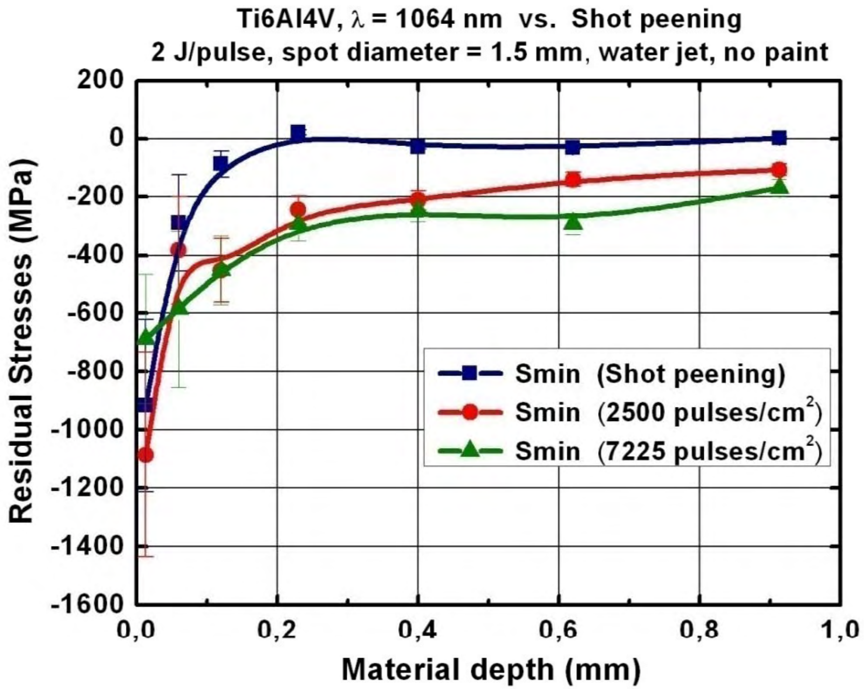
Pulse density (cm^{-2})	C (mm/cycle)	M (dimensionless)
0 (No LSP treatment)	$4x10^{-13}$	7.664
900	$8x10^{-13}$	6.818
1350	$2x10^{-11}$	5.733
2500	$3x10^{-10}$	4.723

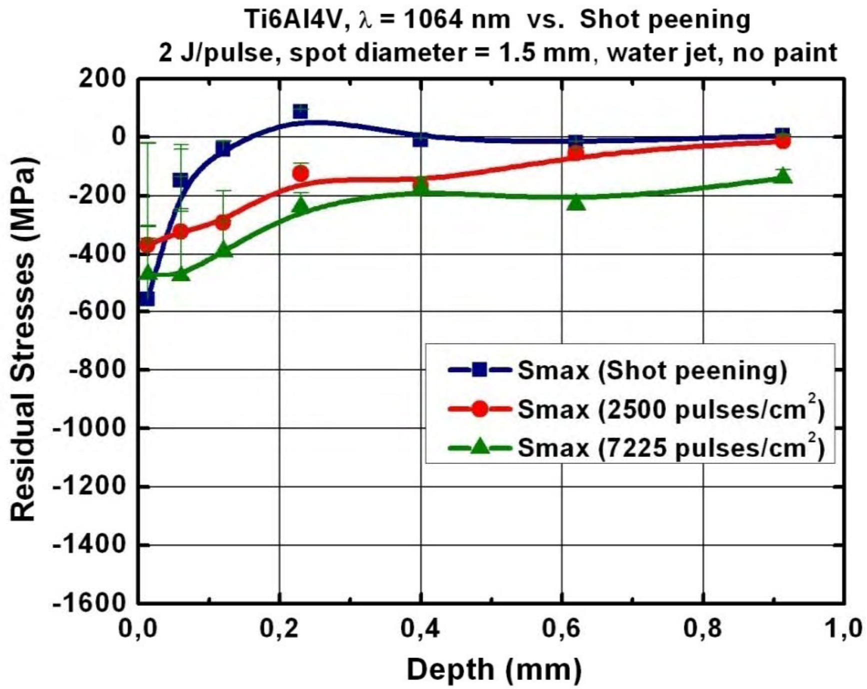
Rubio-González, C. et al.: Mat. Sci. Eng. A., 386 (2004) 291-295

EXPERIMENTAL RESULTS

Residual Stresses (According to ASTM E837-08)

Ti6Al4V: Comparison LSP-Shot Peening





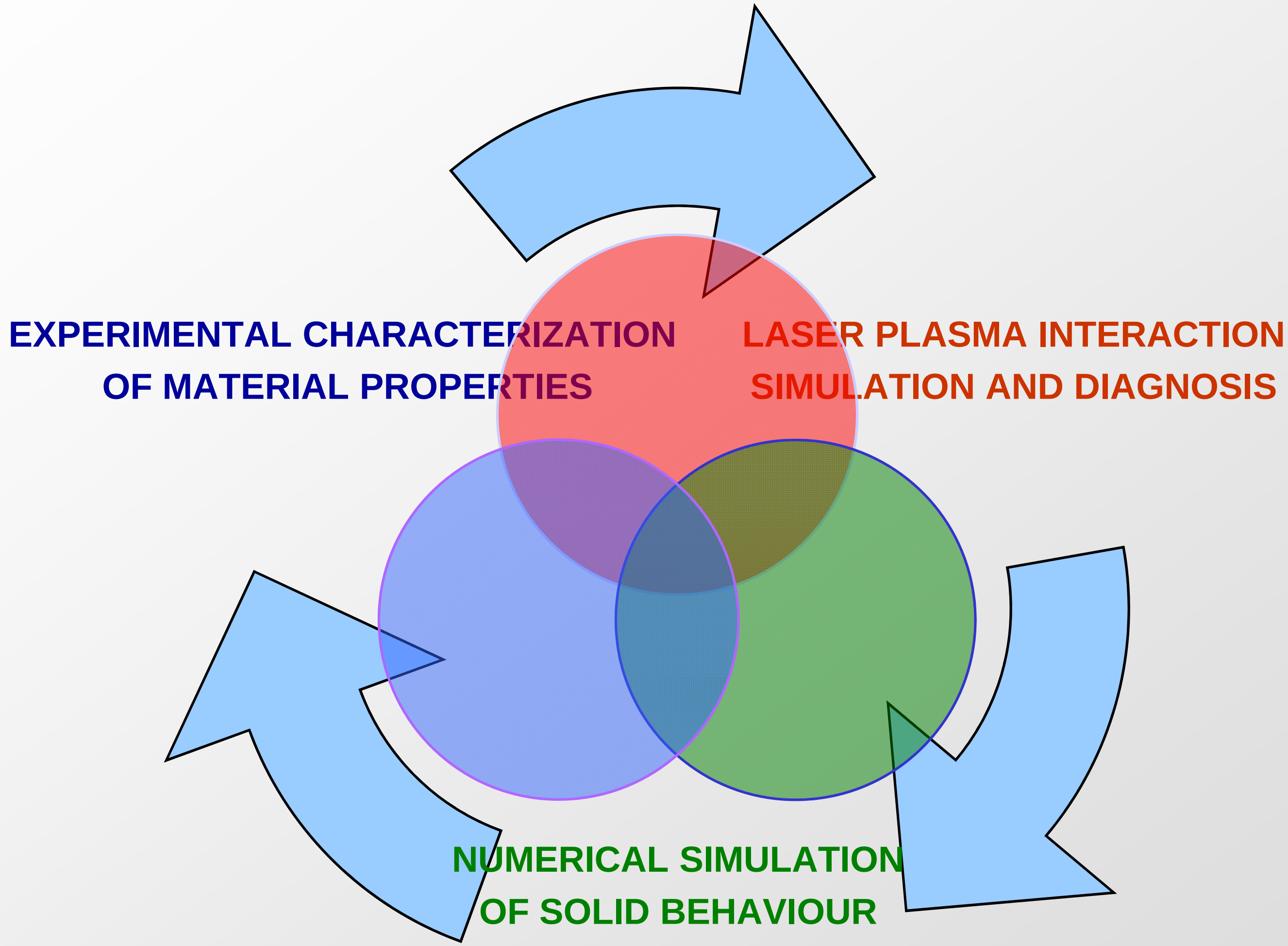
Substantial improvement in Residual Stresses Field in Ti6Al4V vs. to Shot Peening

Decisive improvement in protected depth reached in Ti6Al4V for different irradiation intensities

DISCUSSION AND OUTLOOK

- Important surface resistance and life cycle extension improvements in critical high reliability components by LSP have been experimentally demonstrated.The associate predictive assessment capabilities needed for adequate process design have also been developed and used for theoretical-experimental contrast.
- In view of the important improvements reached in wear behaviour, surface roughness (precursor of improved corrosion resistance) and fatigue life (all of them resulting from the deep compressive residual stresses fields introduced by the process), the LSP technique has to be recognized as a key technology for the enhancement of materials and systems durability and reliability.
- Important technological implementations of LSP in the aerospace, automotive, nuclear and biomedical sectors are under course, anticipating relevant improvements in service reliability and in material preservation and (eco-friendly) efficient use.

7. DISCUSSION AND OUTLOOK



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LSP: An Emerging Sustainability Supporting Technology